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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

MARCH 1960

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THE NINETY-FOURTH ANNIVERSARY LUNCHEON, 12th JANUARY 1960

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working pilot

The IFALPA delegate speaking to the ICAO Special Meeting, Montreal, February 1959

I should like to describe what we have been able to do using Radar for departures. Four aircraft taxi out at the same time. They are fully loaded, it is a hot night so they have an immediate problem. After take-off Departure Control wants immediate contact so we give them a call. Number 2 aircraft takes off two minutes later, and receives the same clearance until he picks up Radar Departure, who say " Turn left heading 050° "—now this is into inbound traffic, which means he will require continuous attention from Control to make sure he picks his way safely through the incoming traffic. Aircraft number 3, two minutes later, same as before, except when he picks up Radar Control, The Controller says " hold 4,000 ft. heading 130°," (he has vectored him off so as to clear the way for aircraft number 4). Aircraft number 4 receives the same departure, but he is told to hold 3,000 ft., and the Radar Controller's attention will also be especially directed towards him because he is bucking the flow of traffic in a place where he does not properly belong.

With regard to the overall achievement, we have now vectored four aircraft into a single airway. Only one of them has achieved the altitude he wanted, and unfortunately he will have to come down through the altitude of the others. Radar is a marvellous device, and it has solved many of our problems, but it is *not* a navigational aid. An area coverage system would not solve every problem, but it would provide the capability of outbound tracks that would take us immediately out of the area from whence discrete tracks could be drawn giving lateral separation of a safe order. This is a problem which is incidental to the use of single track airways, and we feel **it can be solved by lateral separation which should be made available through pictorial presentation coupled with area coverage.**

THE NAVIGATION SYSTEM FOR THE JET AGE

THE DECCA NAVIGATOR COMPANY LIMITED LONDON

Journal of

THE ROYAL AERONAUTICAL SOCIETY

IN WHICH ARE INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS
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All communications for publication in the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., F.R.Ae.S., Hon.F.C.A.I., F.I.A.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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(Founded 1866)

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NOTE: Under the revised By-Laws, allowed on 11th January 1960, the President of each Division and the Chairman of each Section of the Society is a Member of Council by reason of his office.

NOTICES

Annual General Meeting, 5th May 1960

NOTICE IS HEREBY GIVEN that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday 5th May 1960, at 5.30 p.m., in the Offices of the Society, 4 Hamilton Place, London W.1.

Agenda

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheet and Income and Expenditure Accounts of the Royal Aeronautical Society and Aeronautical Trusts Limited for the year ended 31st December 1959.
3. To receive the names of those elected to Council for the years 1960-1963.
4. To elect the Auditors for the year 1960.
5. Any other business.

By Order of the Council,
A. M. Ballantyne,
Secretary.

NOTE: In accordance with the By-Laws any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served after the meeting.

General Meeting of Voters of the Society, *see* p. XV.

Nomination of Candidates for Council

The following is an extract from the amended By-Laws.

(A) *Composition of Council*

The Council shall consist of the President, the three most recently retired Past-Presidents who are willing and able to serve, the President-Elect, the President of each Division, and twenty-one ordinary members of Council. In addition the Chairman of each Section shall be a member of Council by reason of his office, if he is not already a member of Council.

(C) *Ordinary Members of the Council*

The twenty-one ordinary members of the Council shall be nominated and elected among the members of the Society. At the date of their election at least ten shall be Fellows, and one each at least shall be an Associate Fellow and an Associate. At least one other shall be a Graduate, unless a Graduate is already *ex-officio* member of Council as Chairman of a Graduates' and Students' Section of the Society.

Of the ordinary members of the Council that number necessary to create seven vacancies shall retire at each Annual General Meeting. Subject to the provisions of this By-Law as to regraded members the retiring members shall be those with the longest service since their last election. A retiring member shall be eligible for re-election.

Nominations of candidates for election to the Council must be received by the Secretary not later than the tenth day of April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination form shall be signed by one proposer and two seconders, all of whom shall be Voters.

Nomination forms may be obtained from the Secretary.

Elliott Memorial Prize

The Elliott Memorial Prize for the first term in 1960 has been awarded to Leading Aircraft Apprentice K. A. Wright, and will be presented at the Halton Graduation Prizegiving on 13th April 1960.

Closing of the Library

Because of alterations within the building, in connection with the Lecture Theatre, the Library will be closed from the beginning of March and will probably not be in full operation again until some time in August.

Members will be able to borrow books by applying to the Librarian and a limited reference service will be available through the Librarian's office. Reading space will be provided outside the Library.

The inconvenience to members is regretted sincerely but, is unavoidable.

The Forty-Eighth Wilbur Wright Memorial Lecture

The Forty-Eighth Wilbur Wright Memorial Lecture will be held at the Institution of Mechanical Engineers, Birdcage Walk, S.W.1, on Thursday, 19th May 1960 at 6 p.m. (Tea at 5.30 p.m.). The lecture, entitled "Mathematics and Aeronautics," will be given by Mr. M. J. Lighthill, F.R.S., Director of the Royal Aircraft Establishment, Farnborough.

Second International Congress of the Aeronautical Sciences

The Second International Congress of the Aeronautical Sciences will be held in Zurich, Switzerland from 12th to 16th September 1960.

Full details will be published in the April Journal.

Application forms may be obtained from the Secretary, The Royal Aeronautical Society, 4 Hamilton Place, W.1.

Honours Awarded to Members

U.S. Department of Defense Medal

Wladimir A. Reichel, *Associate Fellow*, has been awarded the top honour for exceptional meritorious service to the U.S. Department of Defense in the field of aircraft instruments.

Cumberbatch Trophy for Air Safety

J. Martin, *Fellow*, has been awarded the Cumberbatch Trophy for Air Safety by the Guild of Air Pilots and Air Navigators. Mr. Martin designed the Martin-Baker ejection seat.

Rocket Propulsion Symposium, 1961

A symposium on rocket propulsion sponsored by the Society, the British Interplanetary Society and The College of Aeronautics is to be held at Cranfield from 6th to 7th January 1961. Details will be announced later.

The Branches

Branch Secretaries are reminded that any information and news which would be of interest for the Branches' page in the Journal will be welcomed. Information should be sent to the Editor.

Aircraft Gas Turbine Theory and Design

A short course on Aircraft Gas Turbine Theory and Design will be held at the College of Aeronautics from 16th May to 3rd June 1960.

The course will deal mainly with performance, systems, turbomachine aerodynamics and related design topics, but will include some experimental work on engines. Fees are £70 inclusive of full board and residence.

Details and enrolment forms may be obtained from the Warden, The College of Aeronautics, Cranfield, Bletchley, Bucks.

DIARY

LONDON

24th March

MAIN LECTURE—Engines for Supersonic Air Liners. Dr. R. R. Jamison and R. J. Lane. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea 5.30 p.m.)

25th March

MAN POWERED AIRCRAFT GROUP LECTURE—Aerodynamics of Man Powered Flight with special reference to Inflatable Wings. D. Perkins. Library, 4 Hamilton Place. 7 p.m.

7th April

MAIN LECTURE AT COVENTRY BRANCH—The Optimum Size of a Rocket Engine. J. E. P. Dunning. New Lecture Theatre, Herbert Art Gallery and Museum, Jordan Well, Coventry. 7.30 p.m.

22nd April

AGRICULTURAL AVIATION GROUP LECTURE—Pilot Training. Capt. Richard Bradbury. Library, 4 Hamilton Place. 7 p.m.

5th May

ANNUAL GENERAL MEETING—4 Hamilton Place. 5.30 p.m. GENERAL MEETING. 6 p.m.

ROTORCRAFT SECTION

8th April

Experiences with an Operational Heliport. R. A. C. Brie. Library, 4 Hamilton Place. 6 p.m.

GRADUATES' AND STUDENTS' SECTION

6th April

Thirty Years of Aeronautical Journalism. Thurstan James. Library, 4 Hamilton Place. 7.30 p.m.

BRANCHES

21st March

Henlow—Visit to the Laboratories of the Aircraft Research Association.

22nd March

Cambridge—Film Show. No. 1 Lecture Hall, Cambridge University Engineering Laboratories. 8.15 p.m.

Luton—Annual General Meeting. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

23rd March

Reading—Undercarriage Design Problems. J. Perdue and H. Pendlebury. Top Canteen, Western Manufacturing (Reading) Ltd. 6 p.m.

Weybridge—The VC10. E. E. Marshall. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

25th March

Bristol—Annual General Meeting and Film Show. Filton House. 6 p.m.

Hatfield—Annual Dinner.

Swindon—Annual Buffet Dance. Goddard Arms.

30th March

Brough—Artificial Satellites. Dr. L. R. Shepherd. Royal Station Hotel Writing Room. 7.30 p.m.

Hatfield—Ballistic Vehicles. G. K. C. Pardoe. de Havilland Restaurant. 6.15 p.m.

Preston—The Salvage of "The Empress of Canada." Capt. C. R. Colbeck. R.A.F.A. Hall. 7.30 p.m.

Southampton—Annual General Meeting. Talk by P. Norman. Engineering Lecture Theatre, University of Southampton. 8 p.m.

31st March

Yeovil—Refrigeration. Dr. E. W. Still. Park School, Park Road. 7.30 p.m.

4th April

Boscombe Down—Film Show. Lecture Hall, A. & A.E.E. 5.30 p.m.

Cambridge—Lecture by Wing Cdr. R. P. Beamont. No. 1 Lecture Hall, Cambridge University Engineering Laboratories. 8.15 p.m.

Derby—The Vickers Vanguard. G. F. H. Hemsley. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.

5th April

Glasgow—Annual General Meeting. Royal College of Science and Technology. 7.15 p.m.

Luton—Guidance and Inertial Navigation. E. G. C. Burt. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

6th April

Christchurch—Supersonic Transport Aircraft. Dr. R. G. Thorn. King's Arms Hotel. 7.30 p.m.

Reading—Annual General Meeting and Film Show (The Kitimat Story). Top Canteen, Western Manufacturing (Reading) Ltd. 6 p.m.

Swindon—Experiences of an Airline Pilot. Capt. O. P. Jones. The College, Victoria Road. 7.30 p.m.

7th April

Cheltenham—Annual General Meeting and Film Show. St. Mary's College. 7.30 p.m.

Coventry—MAIN SOCIETY LECTURE—The Optimum Size of a Rocket Engine. J. E. P. Dunning. New Lecture Theatre, Herbert Art Gallery and Museum, Jordan Well, Coventry. 7.30 p.m.

Isle of Wight—An Astronomer Looks at Space Travel. A. F. Collins. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, East Cowes. 6 p.m.

London Airport—Annual General Meeting and Brains Trust. B.E.A. Viking Centre Cinema, London Airport. 6 p.m.

13th April

Brough—Annual General Meeting. Royal Station Hotel Small Lecture Hall, Hull. 7.30 p.m.

Chester—Ram-jets. M. A. Needham. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

Weybridge—Structural Aluminium Alloys for High Speed Flight. Dr. W. M. Doyle. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

14th April

Belfast—Annual General Meeting. Short Brothers and Harland Ltd., Supervisors' Club, Herbert House, Belmont Road, Belfast. 7.30 p.m.

Glasgow—Graduates' and Students' Section—Annual General Meeting and Debate, Engineering Building, University of Glasgow. 7.30 p.m.

15th April

Merthyr Tydfil—Instrumentation from the Pilot's Point of View. Capt. T. Farnsworth.

20th April

Reading—The Radio Telescope. Dr. H. P. Palmer. Top Canteen, Western Manufacturing (Reading) Ltd. 6 p.m.

21st April

Yeovil—Junior Paper Evening. Park School, Park Road. 7.30 p.m.

22nd April

Birmingham and Wolverhampton—Film Night. The Engineering Centre, Birmingham. 7.30 p.m.

27th April

Christchurch—Annual General Meeting. Operational Problems in Supersonic Flight Testing. Wing Cdr. R. P. Beamont. King's Arms Hotel. 7.30 p.m.

Coventry—Annual General Meeting and Films. Herbert Art Gallery. 7.30 p.m.

Hatfield—Supersonic Transports. D. G. Brown. de Havilland Restaurant. 6.15 p.m.

Preston—From Aviation to Astronautics. J. E. Allen. Queen's Hotel, Lytham. 7.45 p.m.

Weybridge—Annual General Meeting. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

28th April

Yeovil—Annual General Meeting. Park School, Park Road. 7.30 p.m.

GENERAL MEETING OF VOTERS OF THE SOCIETY

NOTICE IS HEREBY GIVEN that a General Meeting of Voters of the Society will be held at 4 Hamilton Place, London, W.1, on Thursday the fifth day of May at six o'clock in the afternoon for the purpose of considering and if thought fit passing the following Resolution:

"THAT the definition of the words "The Society" in By-Law 1 of the By-Laws allowed the 11th January 1960 be amended by adding the words "and the Helicopter Association of Great Britain" after the words "Institution of Aeronautical Engineers."

By order of the Council.

A. M. Ballantyne

Secretary.

Dated the 7th day of March 1960.

Shell Plastics Design Competition

The Shell Chemical Company Ltd. announce a Plastics Design Competition. Prizes will be awarded "for original designs of any article or appliance for the industrial, domestic, institutional or public services market which could with advantage be made wholly from or incorporate a major proportion of either Shell Polypropylene or Shell High Density Polyethylene. Prizes will be awarded for the best design, regardless of which material is used for it."

The prizes are:—First £500, Second £300, Third £200. Entrants must be resident in the United Kingdom or the Irish Republic; there is no age limit.

Entry forms and a wallet containing details of the properties of the two materials are available from The Plastics Division, Shell Chemical Company Ltd., 170 Piccadilly, London, W.1. The closing date for entries is **30th June 1960.**

One Year Post-Graduate Course in Fluid Mechanics

The College of Aeronautics will hold a post-graduate course in Fluid Mechanics from October 1960 to July 1961. Successful students will be awarded the Diploma in Advanced Engineering.

The tuition fees will be:—British Students £75, Commonwealth Students £250, Foreign Students £350. The residence fee, inclusive of full board during the terms, will be £126 10s. 0d. Students may apply for grants from the College Bursary Fund.

Full details and application forms may be obtained from The Warden, College of Aeronautics, Cranfield, Bletchley, Bucks.

Whitworth Foundation Awards, 1961

The Ministry of Education invites applications for Whitworth Foundation Awards. Three Fellowships, valued at £1,000 a year, and three Exhibitions of £100 are offered for 1961.

The awards are open to British subjects over 25 years of age who have not previously held a Fellowship or a Senior Whitworth Scholarship. Candidates must have a university degree in engineering, a Diploma in Technology (Eng.), or a Higher National Diploma or Higher National Certificate in engineering with at least two distinctions.

The closing date for applications is **31st July 1960.** Full details and entry forms (Forms 50 and 51 F.E.) may be obtained from the Secretary, Ministry of Education (F.E.1 (C)), Curzon Street, London W.1.

Flight Test Instrumentation Symposium

A Flight Test Instrumentation Symposium will be held at the College of Aeronautics from 7th to 9th April 1960.

The registration fee for the course will be 10s. The inclusive cost of accommodation at the College from lunchtime on 7th April to lunchtime on 9th April is 4 gns.

Further details and application forms may be obtained from M. A. Perry, Esq., Lecturer in Instrumentation, Department of Flight, The College of Aeronautics, Cranfield, Bletchley, Bucks.

James Clayton Lecture

On 21st April Dr. S. G. Hooker, O.B.E., *Fellow*, is repeating in Birmingham his James Clayton Lecture "The Future of Air-Breathing Engines in Aviation," which he gave to the Institution of Mechanical Engineers in London on 16th December last. Members of the Society are welcome to attend the lecture which will be held in the Great Hall, Mathew Bolton Technical College, Suffolk Street, Birmingham, at 6 p.m. Tickets are not required.

News of Members

E. A. Allcut (*Fellow*), Professor Emeritus of Mechanical Engineering, University of Toronto, has been appointed a Commissioner of the Ontario Fuel Board.

W. H. Arklay (*Associate Fellow*) formerly Engineer II, working on Guided Weapons Test Vehicles, Royal Aircraft Establishment, is now a Senior Engineer with the United Kingdom M.O.A.S. at W.R.E., Australia.

D. S. Bancroft (*Associate Fellow*) formerly Assistant Chief Designer, F. G. Miles Ltd., is now Managing Director, Acrow (Reinforced Plastics) Ltd.

A. Neville Barber (*Associate Fellow*) formerly Head of Technical and Design Engineering Department, Hatfield Technical College, is now Vice-Principal and Head of the Department of Engineering and Metallurgy, The Technical College, Workington.

J. W. Bean (*Associate Fellow*) formerly an Intermediate Stressman, de Havilland Aircraft Co. Ltd., is now a Stress Engineer, Vickers-Armstrongs (Aircraft) Ltd., Hurn.

Flt. Lt. D. Biltcliffe (*Associate Fellow*) formerly in the Control Division of the Guided Weapons Department, Royal Aircraft Establishment, is now a member of No. 50 Staff Course at the R.A.F. Staff College, Bracknell.

R. H. Botterill (*Associate Fellow*) formerly Director and Executive Vice-President of Vickers-Armstrongs Inc.,

Arlington, U.S.A., is now Service Controller at Vickers-Armstrongs (Aircraft) Ltd., Weybridge. He remains a Director of the American Company.

W. H. BOYD (*Associate*) formerly Constellation Technical Officer, B.O.A.C. London Airport, is now Engineering Superintendent, W.A.A.C. (Nigeria) Ltd.

M. J. BRENNAN (*Fellow*) Chief Engineer, Folland Aircraft, has joined the Board of Directors.

S. BUCHANAN (*Associate Fellow*) formerly Senior Lecturer in Aircraft Structures, R.A.E. Technical College, Farnborough, is now Principal Lecturer in the Department of Aeronautical Engineering, Northampton College of Advanced Technology.

Wing Cdr. A. D. BUTTON (*Associate Fellow*) formerly at the R.A.F. Technical College, Henlow, is now Command Education Officer, British Forces, Arabian Peninsula.

J. E. CURTIS (*Associate Fellow*) formerly Assistant Development Engineer, Armstrong Siddeley Motors Ltd., is now a Flight Project Engineer, Bristol Siddeley Engines.

PETER J. CUTT (*Associate Fellow*) formerly a Stressman, Vickers-Armstrongs (Aircraft) Ltd., has been appointed Chief Stressman, Technical Designs, Guildford.

Flt. Lt. B. DICKINSON (*Associate Fellow*) formerly at R.A.F. Cranwell, is now Assistant Technical Instructor, Empire Test Pilots' School, Farnborough.

G. D. FORBES (*Associate Fellow*) formerly Design Draughtsman on Engine Installation, de Havilland Aircraft of Canada Ltd., is now a Tool Engineer, Pioneer Engineering and Manufacturing Co., Detroit.

Sqn. Ldr. J. FORD (*Associate Fellow*) formerly on the Staff of the Flag Officer, R.N.A.S., Arbroath, is now at the Air Ministry, Department of the Director General, Technical Services.

J. H. FORRINGTON (*Associate*), formerly General Manager of D. A. Gunn (Engineering) Ltd., has been appointed to the Board.

H. C. HARRISON (*Associate Fellow*) formerly Engineering Director, Flight Refuelling, is now Production Director, Burcat Manufacturing Co. Ltd., Rustington.

N. D. HOLDSWORTH (*Companion*) formerly a Laboratory Assistant, English Electric Co. Ltd., is now an Equipment Engineer, English Electric Aviation, Warton.

E. E. JANSEN (*Associate*), formerly Operations Planning Officer, Qantas Empire Airways Ltd., is now a Technical Officer (Computing Section), Reactor Physics Dept., Australian Atomic Energy Commission, Lucas Heights, N.S.W.

D. G. MACWILKINSON (*Student*) formerly an Aerodynamicist, D. Napier and Son Ltd., Luton, is now a Project Superviser, Aircraft Research Association, Bedford.

H. W. R. A. MILLER (*Associate Fellow*) formerly Inspector in Charge, A.I.D., Rotax Ltd., is now Principal Regional Inspector, A.I.D., South Eastern Regional Office.

T. G. J. MOAG (*Graduate*) formerly a Development Engineer, Precision Engineering Division, Short Bros. and Harland Ltd., is now a Lecturer in the Mechanical Engineering Department, College of Technology, Belfast.

Sqn. Ldr. J. N. QUICK (*Associate Fellow*) formerly at R.A.F. Halton, is now Chief Technical Instructor, Empire Test Pilots' School, Farnborough.

J. H. RISDON (*Associate Fellow*) formerly Senior Technical Assistant, Research Department, D. Napier and Son Ltd., Acton, is now a Patents Examiner, Board of Trade.

ERIC ROSE (*Associate Fellow*) formerly at A. V. Roe and Co. Ltd., Chadderton, is now a Lecturer in Servomechanisms and Automatic Control in the Applied Mechanics Department, Sheffield University.

A. SCIBOR-RYLSKI (*Associate Fellow*) formerly at Hatfield Technical College, is now Lecturer in Aerodynamics, Aeronautical Engineering Dept., Northampton College of Advanced Technology, London.

D. A. SHARP (*Graduate*) formerly Defence Scientific Officer, Canadian Armament Research and Development Establishment, is now Stress Engineer, Advanced Project Group, Hawker Siddeley Aviation Ltd.

M. A. SIDDIQUI (*Associate*) formerly a Technical Assistant, Sperry Gyroscope Co. Ltd., is now a Research Engineer (Research and Development).

N. SULLIVAN (*Associate Fellow*) formerly Equipment Engineer, Sperry Gyroscope Co. Ltd., is now Engineering Superintendent (Automatic Controls) in the Aeronautical Department.

GORDON WANSBROUGH-WHITE (*Associate*), at present with Bristol Aircraft Ltd., will join the Metal Industries Group on 1st April as Assistant to the Group Organisation and Methods Officer.

H. J. WEBB (*Associate Fellow*) formerly with the Engineering Division, A. & A.E.E., Boscombe Down is now Resident Technical Officer (A), Bristol Aircraft Ltd.

ELECTIONS

The following is a list of elections and transfers of membership of the Society:—

Associate Fellows

Frank William Ashmole (*from Student*)
Ronald Edward Bird (*from Associate*)
Cedric Arthur Bishop
Roy Stanley Bradley
Frederick Alexander Burls
Robert Alfred Copsey Carter (*ex Student*)
Laurence Joseph Clancy (*from Graduate*)
Robert Cockburn
Harry Cooper
Frederick George Cross
Edward Thomas Curran (*from Student*)
Peter John Cutt (*from Graduate*)
Pierre de Guillenchmidt
Derek Alfred Doel
Donald Edward Dormer (*from Associate*)
Glenroy Joffre Evans
John Langmuir Flintoff
Cyril John Digby Fowle
Peter Girgis
Peter John Goulthorpe
Herbert William Griffiths
John Charles Harrington
Michael John Harris (*from Graduate*)
Geoffrey Stanley Holister (*from Graduate*)
Ooriapadical Cherian Koshy
Kenneth Roy Liversage (*from Graduate*)
Andrew McClements
Thomas Gilbert Mahaddie
Arthur Thomas Marsh
John Owen Mathews
Brian William Plenderleith (*ex Graduate*)
Peter Marcus Ray (*from Graduate*)
Stanley Arthur Llewellyn Rees
Idris Roberts
Wilfred Harold Sear
Stanley Douglas Singleton
Colin Edward Spedding (*from Graduate*)
Christopher John Hamshaw Thomas (*from Graduate*)
David Eric Turnbull (*from Graduate*)
James William Tuson
Reinier Joseph Van der Harten
John White
Douglas Anderson Wilkinson
Robert Eric Young

Associates

Cyril Cresswell
Colin James Holland Dear
Ivon Arthur Frederic Donnelly
Herbert John Draper
Thomas Henry Dudley
Richard Cecil Edmonston-Low
Thomas Peter Frost
Frank Anthony Rupert Garner
Michael Frank Higginson (*from Student*)
John Edwardes M'Kenzie-Hall
David Murdoch McLaren
Alfred Marfleet
Richard John O'Connell
George Cowdery Webb

Graduates

Thomas Desmond Arthurs
Martin Morris Black
James Counihan (*from Student*)
William Barron Dent (*from Student*)
Donal F. Downing
Peter Richard Felton
Simon Munro Fraser
Michael George Hall (*from Student*)
David Weston Harvey
David Hyde (*from Student*)
Sorachai Jantrpan
Andrew Kedar (*from Student*)
Charles George Keil (*from Student*)
Michael Lisandro Lopez (*from Student*)
George Sidney Lowes
Richard Stephen Capell Lowick
George Gordon Lucas (*from Student*)
Robin Anthony Newnham (*from Student*)
Hedley Patrick O'Sullivan (*from Student*)
Barry Pitkin
David James Pollard (*from Student*)
John Knivett Ratcliffe
Nilkanth Janardan Shendge (*from Student*)
Devinder Singh
Ralph George Thomas
Denis Rutherford West

Students

Christopher Robin Abbess
Sydney Adams
John Kemp Appleford
Brian Barry
Sheila Mary Birchenough
Ronald George Bustin
Harvey Warren Cooke
Christopher John Orme Dudfield
John Robert Gleadle
John Michael Hall
Trevor George Hird
Peter Scott Howes
Edward Tunnard Jackson
Douglas Kaye
John Richard Evitt Lee
Gordon Ernest Lee-Steere
Edward James Lovesey
Michael Henry Marsden
John Alfred Lloyd Norris
John Kenneth Parry
Virendrakumar Chaturbhai Patel
Colin Stanley Pollard
Neil John Beaumont Ritchie
George Albert Roscilli
Bik Kwong Sum
John Charles Trevett
Mark Vardy
David James Walters
Robert Alexander Watt
John White
Gilbert Hugh Wright

Companions

Antony Cecil Billingham
Victor Edward Creighton Brooks (*from Graduate*)
Kenneth Noel Crawford
Frank Ernest Freestone
Robert Gibling
Norman John Hulbert
Aubrey Joseph Jackson
Cyril Raymond Jeffs
Malcolm Lowe
William Arthur George Marsh
Neil Balfour Morris
Birendra Nath Mukherjee
Thambihalli Ramakrishnasastry Venkata Subbu
Jocelyn Walker
Roger Henry White-Smith
G. A. Yarotski
John Humphery Yorath

Lecture Summaries

Rotorcraft Section

SOME BRITISH RESEARCH ON THE AERODYNAMICS OF POWERED LIFT SYSTEMS

Dr. J. WILLIAMS, M.Sc., Ph.D., A.F.R.Ae.S.

Given on 4th March 1960

The lecture discusses some recent British research on the aerodynamics of methods for providing adequate lift at low and zero forward speeds. The work will be classified under the four broad headings of Direct Jet Lift (turbo-jet and turbo-fan), Propeller Lift (tilt wing and deflected slipstream), Jet Flaps, and Boundary Layer Control (blowing and suction). The first two items are relevant to both V.T.O.L. and S.T.O.L. application, but the last two are essentially restricted to operation under S.T.O.L. or transition conditions.

Direct Jet Lift here implies round jets directed vertically downwards, in an attempt to provide lift augmentation roughly equal to the vertical component of the rate of ejection of momentum. However, the mainstream flow over adjacent surfaces may be markedly affected by the presence of the jet efflux or intake suction, while at zero mainstream speed the flow pattern induced by the jet can be significant near the ground. Such interference effects can vary appreciably with the ratio of jet exit area to wing planform area (or wing loading to disc loading), *i.e.* for a change from V.T.O.L. installations with high velocity jets (pure turbo-jet) to low velocity jets (fan systems). The intake flows associated with fan-lift systems in particular need special consideration, both as regards their effects on the internal surface flows and the internal flow requirements at the fan disc.

Propeller Lift is achieved from turning the thrust of the propulsive propellers to give a lifting component, either by tilting the propeller-wing combination towards the vertical, or by deflecting the propeller slipstream using an elaborate flap system. With the tilt wing a simple slotted flap is often incorporated to assist transition between hovering and forward flight, while with the deflected slipstream arrangement a large wing-ground angle is usually needed to deflect the thrust vertically without undue loss of efficiency.

Jet Flaps imply that a large proportion of the efflux of the installed gas turbines is elected as a plane sheet over the wing trailing edge at an angle to the mainstream. This represents an attempt to integrate the propulsive and lifting systems, the vertical component of the jet momentum being magnified several times by the "pressure lift" generated on the wing surface. The incorporation of a small trailing edge flap, whose angle can be simply varied, is intended primarily as a practical method of altering the jet-angle without varying the inclination of the blowing slot.

Boundary Layer Control normally uses a small proportion of the installed engine power to induce blowing or suction at the wing surface, for the prevention of flow separation which tends to occur on the upper surface of the wing nose and the trailing edge flap knee. This represents an attempt to attain the ideal lifting efficiency of the system corresponding to potential (inviscid) flow.

The lecture mostly refers to research work carried out at the R.A.E. and the N.P.L., but some of the work at firms and universities is also mentioned where the information has been made available. Attention is especially drawn to the present state of aerodynamic knowledge in relation to possible V.T.O.L. and S.T.O.L. systems and to some major aerodynamic problems which need further study.

Symposium on Vehicle and Instrumentation Problems in Upper Atmosphere Research—five papers.

Held on 11th March 1960

SKYLARK

J. F. HAZELL

Skylark is a rocket designed for research at altitudes up to 100 miles with instrument payloads of 150 lb., and was the outcome of discussions in the Royal Society starting in 1953 and culminating in 1955 with Treasury agreement for a joint Royal Society/Ministry of Supply programme of upper atmosphere research.

The vehicle is 25½ ft. long, 17½ inches in diameter, weighs about a ton and is powered by a Raven solid propellant motor which produces 12,000 lb. thrust for about 30 seconds. It is stabilised in flight by three fixed fins.

Rockets launched near to the vertical with low acceleration present very serious dispersion problems. These have been successfully overcome by careful attention to jet and aerodynamic misalignment of the motor and vehicle, special techniques for wind corrections, and the use of a 100 ft. launcher. An unexpected roll resonance phenomena has been encountered which can lead to instability towards end of burning unless the roll rate is kept to a very low level.

Information from instruments within the vehicle is usually transmitted to the ground using a standard 465 Mc/s telemetry sender. When necessary, the head can be recovered by parachute so that tape and mirror galvanometer systems can be used, or experiments made requiring X-ray plates, or star photographs for example. The flexibility of the vehicle is illustrated by the wide range of probes, etc., that are being used, *e.g.* spikes for ion probes and magnetometers, jettisoned nose cones to expose photometers or cameras, ejection of devices such as the Birmingham ion cage and deployment of grenades, window and sodium vapour.

An even wider field of experiments will soon be opened when a pneumatic head stabilisation system is introduced. In addition improved Ravens and auxiliary boosts will extend normal Skylark facilities to 140-160 miles altitude while a two-stage version, already constructed, could take a more limited payload to 300-400 miles.

SCIENTIFIC INFORMATION FROM SKYLARK

Dr. R. L. F. BOYD

The programme of scientific studies being carried out in the upper atmosphere, using Skylark rockets, covers a very wide field. Studies of the neutral atmosphere include the ejection of radar chaff ("Window"), grenades, photochemical and photoscattering materials in experiments on wind, temperature and density. The ionosphere is investigated by ion chamber, dielectric probe, Langmuir probe and radio propagation. Filter methods are being used to measure the airglow, counter and emulsion methods to monitor solar X-radiation and ion chambers for ultra violet light from the sun. Astronomy in the ultra violet is being undertaken by sky scanning experiments and photography. The magnetic field in the ionosphere and the flux of micrometeorites are also under investigation. Some of the techniques of this work will be described together with the results of measurements.

METEOROLOGICAL MEASUREMENTS

Dr. G. D. ROBINSON

The methods available for measurement of wind, temperature and density, and composition of the upper atmosphere will be enumerated and the state of knowledge prior to the I.G.Y. briefly reviewed. Below about 100 km. a self-consistent scheme of mean values and seasonal variation emerges, but many details remain to be filled in, and little is known of the tidal motions or of the turbulent fluctuations which are to be

expected on all scales. Some current and projected uses of rocket and satellite-borne equipment will be described.

Above about 100 km. wind measurements are complicated by the existence of electrical forces, but the release from rockets of un-ionised photo-scattering materials is possible and a few results have been reported. Analysis of satellite motions yields density in this region and indicates considerable variations.

The use of observations from artificial satellites in routine weather forecasting is receiving much attention and it is expected that an attempt will shortly be made in the U.S.A. to place in orbit a satellite carrying television equipment for reporting cloud cover. Some of the possibilities and the requirements, *e.g.* in regard to resolution, will be discussed, with the aid of cloud photographs from rocket-borne cameras.

RANGE INSTRUMENTATION PROBLEMS

H. J. HIGGS

Care must be taken in speaking of range instrumentation problems in upper atmosphere research not to create the impression that it is an entirely separate aspect from the probe instrumentation. Too frequently in the past it has been regarded as an everyday laboratory service, whereas it is a fundamental part of the design of the experiment. Fortunately this is not so today as the advent of the overall experiments have highlighted the immense problems of the overall instrumentation systems. The only division line, and this should be lightly drawn, is between the special sensing units (or transducers) detecting the phenomena occurring at the probe and their outputs feeding the data transmission system. The transmitters within the probe, their radiation power, aerial system, electrical supplies and environment control all significantly affect the so called range instrumentation both in character and disposition as much as the actual flight pattern itself.

With this in mind, the range instrumentation problem in upper atmosphere research may be divided into four fields:

(*a*) *Probe location* from both active and passive aspects, *i.e.* guidance and safety, in the first case and subsequent co-ordinate determination (such as in geocentric axes and time) for fixing other observations in the second case.

(*b*) *Data Recovery from the probe* generally by telemetry, possibly by recovery of tapes, photographic plates and samples or by telecommunications with the observer as in Project Mercury.

(*c*) *Observation of Probe induced phenomena* such as the observation of sodium clouds, window, ionisation and wake effects and re-entry luminosity.

(*d*) *Experimental environment, i.e.* the general observation from other instruments of phenomena such as the meteorological conditions, ionospheric state, magnetic field, cosmic ray and solar activity at the time of the probe measurements.

The characteristics and problems of some of the instrumentation in these fields (including the important logistic and communication aspects) are briefly described for three main types of probes—sounding rockets, satellite vehicles, planetary vehicles.

FUTURE POSSIBILITIES

E. C. CORNFORD

The paper discusses some of the advantages and disadvantages of conducting upper atmosphere research in earth satellites rather than in rockets.

It then goes on to survey briefly the future possibilities offered by the American launching vehicle scout, and by launching vehicles based on Blue Streak. The broad performance capabilities and some of the design problems of a British launching vehicle are indicated.

Finally, the main design problems in providing an appropriate satellite environment, including stabilisation and control, power supplies, telemetry, etc., for scientific experiments are outlined.

ENGINES FOR SUPERSONIC AIR LINERS

Dr. R. R. JAMISON and R. J. LANE

To be given on 24th March

The power plant of a supersonic transport aircraft is a component which exerts a major effect on its performance and characteristics so it is important to provide the aircraft designer with a clear picture of the kind of power units he may expect to be able to use in this new context. This paper presents the results of a survey which has been made into the power plant requirements in this field. The whole subject is made most complex by the interplay of many technical, economic and operational factors and it helps to sharpen the focus of the enquiry to concentrate on a specific objective. This has been taken as a commercial transport for the Atlantic stage, London-New York.

The speeds chosen for specific evaluation are Mach numbers of 2, 3 and 4·5, and at these speeds the performance of aircraft engine combinations for a variety of power plants determined. The power plants covered have been:

(*a*) Straight turbo-jets with turbine entry temperatures up to 1400°K.
(*b*) Turbo-jets reheated up to 1800°K.
(*c*) Turbo-jets in combination with ram-jets.
(*d*) Reheated ducted fans.

At each speed and for each engine type the engine-airframe configuration has been optimised for use on the chosen mission profile with full fuel allowance for flight contingencies. Airframe weights have been adjusted for speed, wing loading, kinetic heating and refrigeration requirements and requirements specified for minimum take-off performance and maximum approach speed on landing. By using this procedure the best airframe-engine match has been obtained at each chosen speed by adjustment of cruise height, wing loading and installed thrust capacity. Then by comparing aircraft of the same take-off weight the merits of each case have been expressed as payload. At all the speeds ($M=2$, 3 and 4·5) the best payloads have come out between 10 and 15 per cent of the all-up weight at take-off.

For the Mach 2 aircraft (typifying an aluminium airframe) the best engine is a high pressure ratio high temperature turbo-jet giving a payload of 15 per cent.

At $M=3$ there is a close competition between the reheated turbo-jets and the turbo-jet/ram-jet combination offering a payload of 12 per cent.

At $M=4·5$ there is a clear choice for the combination engine, cruising on ram-jets only with a payload of 10 per cent. On these figures the productivity (or earning capacity) of the aircraft increases with the flight speed.

Where noise at take-off is to be held to a minimum (which may be a dominant factor) a reheated ducted fan is indicated which may offer payloads comparable with the above engines.

Another critical factor is brought in by the choice of altitude for transonic acceleration in relation to its influence on the nuisance of sonic boom. Increased acceleration height means increased engine weight and diminished payload. This is a direct and important economic effect which highlights the need for intensive study of this phenomenon and the evolution of techniques to diminish its influence.

THE OPTIMUM SIZE OF A ROCKET ENGINE

J. E. P. DUNNING, M.A., F.R.Ae.S., M.I.Mech.E.

To be given on 7th April in Coventry

The paper gives a précis of studies made at the Rocket Propulsion Establishment of the Ministry of Aviation to determine the relationship between the specific weight and thrust of a liquid bi-propellant rocket engine.

Although the need for a better understanding of basic phenomena is established, the conclusion is reached that, within the selected premises, the minimum specific weight is achieved at a thrust level near 50,000 lb. The difference in specific weight between engines of 200,000 lb. thrust and 50,000 lb. thrust is only about 10 per cent and this is shown to be equivalent to only one per cent in propellant specific impulse. Although small, it is considered significant that a minimum has been established and this fact is used as an argument to justify the use of clusters of engines (generally four) to provide levels of thrust greater than 100,000 lb.

Rotorcraft Section

EXPERIENCES WITH AN OPERATIONAL HELIPORT

W/Cdr. R. A. C. BRIE, A.F.R.Ae.S., A.F.I.A.S.

To be given on 8th April 1960

This lecture is primarily an account of operational experience resulting from helicopter activities at the Westland London Heliport since it was opened in April 1959.

Despite limitations in size, location and life expectancy, this facility is shown to be a worthwhile experiment capable of producing factual information of a strictly commercial and operational nature.

Statistics are produced relating to user activities and the related financial aspects of heliport construction and operation to meet user requirements.

The Journal of the Royal Aeronautical Society

IN WHICH ARE INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS AND THE HELICOPTER ASSOCIATION OF GREAT BRITAIN

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Some Practical Aspects of Compressor Blade Vibration*

by

E. K. ARMSTRONG, Ph.D., Wh.Sch., and R. E. STEVENSON, M.A.

(Bristol Siddeley Engines Ltd.)

1. Introduction

The object of this paper is to set down an overall picture of the practical aspects of compressor blade vibration. In doing so it is inevitable that a certain content is effectively a repeat of other people's contributions to the subject. The authors make no apology for this and offer the paper as a "state of the art" as practised at Bristol Siddeley Engines Ltd. In bringing together the many relevant issues of this problem, it is hoped that a useful presentation is obtained.

There is little hesitation in indicating the most obvious and important practical aspect of blade vibration as that of the inherent danger of blade failure and it is known that the axial flow compressor is susceptible to complete failure caused by the fatigue of one blade.

The multi-stage axial flow compressor is a highly complex aerodynamic machine with its early and late stages required to operate over wide ranges of incidence and Mach number conditions. To some extent, of course, use of variable geometry can reduce this to less taxing proportions. The aerodynamic environment of front stages has broad boundaries somewhat wider than those relating to rear stages, while middle blade rows generally operate under sensibly constant conditions. This diminishing "severity" of operation, front, rear to middle stage blading is not unrelated to the incidence of blade vibration problems which shows a similar pattern.

A further general aspect of compressor blade vibration is that investigations into the subject essentially receive their impetus from main engine experience. In this way, knowledge tends to be accumulated in isolated areas. Additionally it is often the case that when given an engine vibration problem, the solution must be sought and obtained with the minimum of delay and cost to the engine development programme. Both these factors make the formulation of "design rules" somewhat hesitant. On the other hand, however, practical experience primarily provides the basis for such rules and the more information from different sources which can be assimilated the more pertinent theoretical approaches and supporting research programmes can be pursued.

Experience has shown that rotor blade vibration is more extensive than that on stator blading. All the forms of stator excitation are present on rotor blading and, since additional sources occur in the case of rotor blades, this paper covers this aspect of the subject.

*The 1133rd lecture to be given before the Society—on 8th December 1959.

2. Specification of Vibration

The most serious and, in general, the largest amplitudes of vibration occur in one of the blade's normal modes. During engine development testing over a period of eight to ten years, a number of instances of blade failures have occurred. By fairly rigorous endurance testing backed by strain gauging, it has been shown that more than 90 per cent of these failures can be attributed to vibration in the first or second flexural mode, the first torsional mode or the first edgewise mode. Thus when carrying out a strain gauge investigation it is necessary to measure the amplitude of vibration in each of these modes.

Usually the magnitude of vibration is measured by means of a strain gauge fixed on the blade form. Due to the complicated shape of a blade, especially around the radii of the root section, it is not possible to locate the gauge at the point of maximum stress of a particular mode. Thus the gauge signal must be calibrated in terms which can be related to the fatigue strength of the material. Ideally, by choosing a position of the gauge at which the signal is approximately equal for amplitudes of vibration of the same severity in the four modes, it will be easier to observe the amplitudes associated with each mode.

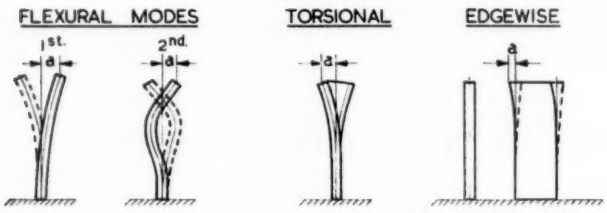
The necessity to calibrate the gauges for each mode led to the adoption of specifying the vibration in terms of amplitude times frequency.

In the case of a uniform cantilever vibrating in one of its normal modes of vibration, it can be shown that the maximum stress on the root section is given by:

$$\sigma_{max} = 2\pi \frac{y}{k} \sqrt{(E\rho)}\, af$$

(*See* Fig. 1 for definition of symbols).

where $\pm a$ is the leading edge tip amplitude of vibration at frequency f in c./sec. It will be seen from this expression that neither the length nor the chord of the cantilever enter as such into the equation. When the maximum stress is equal to the endurance stress, the factor af is solely dependent on the section geometry and the material properties. The carrying out of fatigue tests on blades has shown that the af for failure does



FOR ALL FLEXURAL MODES OF CANTILEVER

MAX. ROOT SECTION STRESS = $\sigma_{MAX.} = 2\pi \frac{y}{k}\sqrt{E\rho}\ af$

k - RADIUS OF GYRATION ROOT SECTION

y - DISTANCE FROM NEUTRAL AXIS TO POINT OF MAX. STRESS

E - YOUNG'S MODULUS ±a - TOTAL AMPLITUDE

ρ - DENSITY f - FREQUENCY

TYPICAL FATIGUE RIG FAILING AMPLITUDES 10^7 CYCLES

	af
ALUMINIUM	±5·5 FT/SEC.
STEEL	±6·5 FT/SEC.
TITANIUM	±11·0 FT/SEC.
GLASS FIBRE LAMINATE	±12·0 FT/SEC.

TYPICAL STRAIN GAUGE POSITION & CALIBRATION

MODE	FREQUENCY - C.P.S	MILLIVOLTS R.M.S. FOR ± 1 FT/SEC
1 F	250	1·2
2 F	952	1·1
1 T	1574	0·85
1 E	1936	0·68

FIGURE 1. Specification of vibration.

not vary much between blades of different designs, but is dependent upon the material. Typical values for 10^7 reversals are:

Aluminium	5·5 ft./sec.
Steel	6·5 ft./sec.
Titanium	11·0 ft./sec.
Glass Fibre Laminates	13·0 ft./sec.

From experimental results in the torsional mode it can also be shown that the form of the relationship used for the flexural modes is also satisfactory in analysing the torsional modes.

In this paper, amplitudes of vibration will be expressed in terms of the product *af* and it may be taken for normal blade designs that amplitudes of vibration are considered serious when they exceed 2·0 ft./sec. in the case of aluminium and steel blading. All the rotor blading considered in this paper has fir-tree root fixings.

When carrying out strain gauge tests it is usual practice to observe initially the signals from four blades per stage. During the analysis, however, and subsequent testing on the engine, only the signals from the two blades showing the largest amplitudes are used.

For the past two and a half years testing has been carried out with the aid of magnetic tape recording and the analysis performed with electrical wave analysers. With these techniques it is advantageous to carry out testing by means of very slow accelerations. The rate normally used is 2,000 r.p.m. per minute. In cases of fluctuating amplitude this type of testing may show differences of peak amplitude measurement when compared to those recorded at steady engine conditions during a period of, say, ten seconds.

3. Types of Vibration

From the results of tests on single stage research compressors and cascade tests of blades, four types of excitation have been observed. When testing blades in engine compressors this experience enables the classification of a particular vibration and suggests special tests to assist in its identification. By knowing the class of vibration and the mechanism of excitation it is then possible to suggest a means of reducing the amplitude.

The character of each of these four classes of excitation will now be described.

3.1. FIXED WAKE EXCITATION

This type of vibration is perhaps the most widely known and understood. In the air flow annulus of the compressor there is generally a number of fixed vanes which carry services to the rotor or support the bearings. The air flow over these vanes will create wakes of low air velocity compared to the remainder of the annulus. As the rotor blade passes through these zones so the aerodynamic force on the blade will be reduced. The frequency of the pulses will be equal to the number of reductions in air velocity times the speed of rotation. Should this frequency or a harmonic be equal to one of the natural frequencies of the rotor blade, then a fairly large amplitude may be built up.

A similar effect occurs in the case of obstructions in the exit annulus of the compressor. Here the nose of the vane gives rise to an increase in local static pressure. This increase is propagated upstream and causes a variation of force on the blade in a similar way to the downstream wake of a vane.

3.2. FLUTTER

The majority of the basic work associated with blade flutter has been conducted on cascades of blades. Vibration in either the fundamental flexural and/or torsional modes has been observed. The mechanism of vibration is one of self-excitation and is due to the shape of the aerodynamic lift or moment/incidence characteristic. If the variation of aerodynamic force on

the blade with a change of incidence, due to the blade's vibration, is such that the force increases for a reduction of incidence, then the vibration will build up. Suitable conditions for self-excitation are in the region of blade stall or in the zone of incidence and Mach number where the cascade becomes choked.

3.3. ROTATING STALL CELL EXCITATION

During performance research testing on an experimental compressor, it was found that the air flow at conditions below the stall conditions of the first rotor blade row broke up into a series of stalled and unstalled patches. One characteristic of the flow was that the stalled zones rotated in the same direction as the rotor but at approximately half the speed. Generally, the number of zones can vary between one and eight and is influenced by the presence of adjacent stages of stator and rotor blading and position on the compressor characteristic. The pattern is fixed by $N/\sqrt{T}$ conditions.

Because the stalled zones consist of low velocity air, the aerodynamic force on the rotor blade will be reduced thus giving rise to a pulsating force as the cells pass the rotor blade. It is therefore possible to build up large resonant vibrations when pulsations or harmonics occur at a blade natural frequency.

As the factors which determine the presence or the number of cells and their speed of rotation are not isolated, so it is not yet possible to predict the excitation likely to be present in a particular compressor stage.

3.4. RANDOM TYPE OF VIBRATION

It is sometimes found that fairly large fluctuating amplitudes are obtained in compressors and cascades not caused by any of the previous methods of excitation. In these circumstances it has been suggested that the vibration is the result of a general buffeting effect due to random disturbances in the air flow. Amplitudes in both the flexural and torsional modes are possible.

4. Engine Vibration

In Section 3 the elementary picture of the classes and mechanism of excitation observed in research rigs was described. We will now consider how these relate to the phases of investigation, identification and treatment of engine blade problems.

4.1. WAKE VIBRATION

All the modes normally examined, *i.e.* the fundamental and the second flexural modes, first torsion and the first edgewise modes, can be excited by wake excitation. Higher modes are also present but, when analysed, it is found that their amplitudes are usually below the accepted level.

4.1.1. *Character of Vibration*

Blade vibration caused by wake excitation exhibits all the characteristics of a classical forced resonance. The amplitudes are fairly steady with time for a set speed and, of course, peak at the resonant speed. Because of slight differences in blade natural frequencies, the resonant speeds for two blades will be correspondingly different. By observing the relative phase difference between two blades, a phase change is seen as each blade passes through its individual resonance.

4.1.2. *Upstream and Downstream Excitation*

Besides the wakes from intake vanes giving rise to blade excitation, it is possible for seriously large amplitudes to be generated from vanes which are downstream of the blade. These vanes may be associated with diffusers into combustion chambers or the services into the intermediate casing of a two spool engine. Usually both intake and intermediate casing vanes have thickness to chord ratios of about 15 per cent and are positioned so that the edge of the vane is about half a vane chord from the rotor blade. Even so, excitation of a serious nature has been experienced on the second rotor row from the obstruction.

4.1.3. *Resonances Removed from Speed Range*

Failure experience and strain gauging have shown that modes likely to cause failure are 1*F*, 2*F*, 1*T* and 1*E* when resonating with the fundamental of the obstruction for the two adjacent rotor rows. Consequently, such resonances are removed from the speed range either by adjustment of the blade frequency or by altering the number of obstructions at the design stage.

As a result of this policy over the past years it has not been possible to investigate the effects of material change and flight condition on vibrations of large amplitude.

4.1.4. *Other Causes of Wake Excitation*

When an engine is free from flutter, rotating stall or random vibration, there remains a vibration characteristic over the whole speed range composed of engine order vibrations (Fig. 2). The engine orders present are apparently unrelated to the obvious geometry of the compressor. All four modes can be excited, but amplitudes seldom peak above 1·0 ft./sec. It is

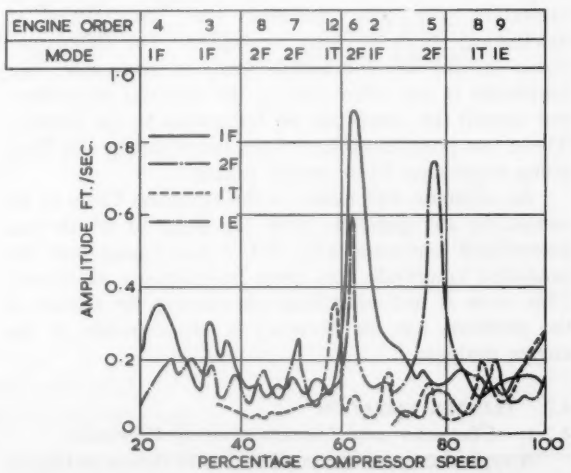


FIGURE 2. Engine order vibration.

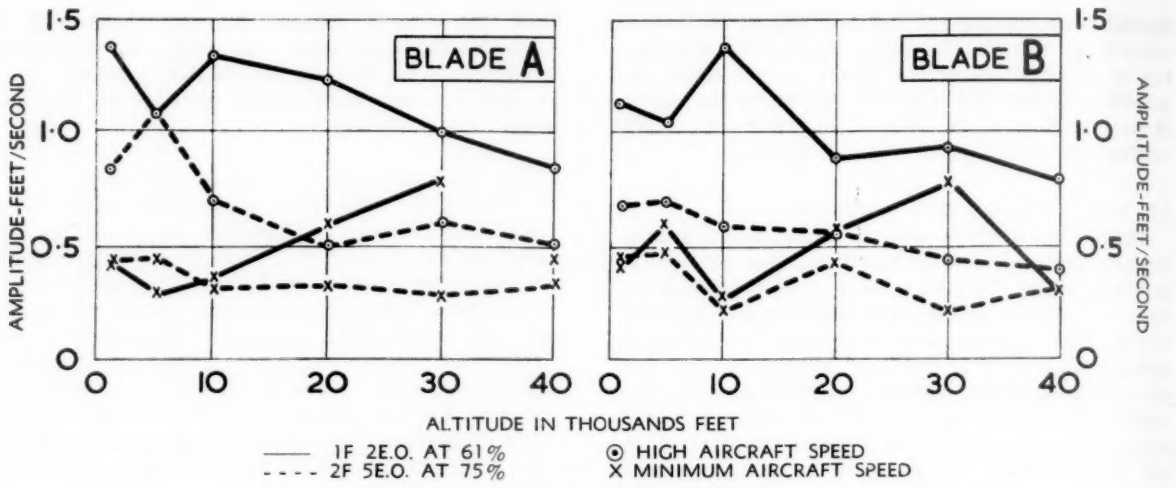


FIGURE 3. Variation of amplitude with altitude.

considered that a source of this excitation possibly lies in intake mal-distributions.

4.1.5. *Effect of Flight Condition*

Figure 3 indicates that there is little change of amplitude of vibration with altitude.

4.1.6. *Change of Blade Material*

The only case when strain gauge tests were carried out with aluminium blades replaced by steel, and where there was an engine order present, little alteration was found in *af* amplitude. The engine order was only indirectly related to the intake geometry in that the most likely source was half the number of the intake vanes. Because of this doubt, however, and the low amplitude (1·0 ft./sec.) the result can only be taken as an indication of the effect of change of material.

4.1.7. *Correlation of Experience with Theory*

Pearson[2] proposed a hypothesis in which the amplitudes of vibration were determined by the balance between aerodynamic damping and the aerodynamic excitation. It was assumed that the effects of mechanical damping were negligible. On this hypothesis it can be concluded that, at resonance, the amplitude is not influenced by the material properties; nor should the amplitude be influenced by air density. These two predictions have been borne out by the foregoing experience from engine testing.

An estimate was made of the vibration likely to be caused by an upstream vane, the wake of which was determined experimentally, but it was found that the predicted amplitude was twice that actually measured. This error is not surprising considering the nature of the problem, but the accuracy is unacceptable to the engine designer.

4.2. FLUTTER VIBRATION

4.2.1. *Character and Identification of Vibration*

A typical case of flutter vibration is shown in Fig. 4. It will be seen that only one mode of vibration is present at the peak; this is found to be the case whether the vibration is of the fundamental flexural or torsional mode. So far a vibration which has been identified as flutter has not occurred in a higher mode of vibration. On a detailed analysis of the strain gauge signals it is found that at moderate amplitudes the blades vibrate at their own natural frequencies. The peak amplitudes of different blades usually occur at the same speed. Often there is a large scatter, greater than 4:1, in amplitudes between blades in the same disc. When the amplitudes are large, it often occurs that the blades vibrate at a common frequency and the scatter in amplitudes round the disc may be reduced.

4.2.2. *Effect of Inlet Guide Vane Setting*

Fundamentally, the most important parameter in determining whether a blade is likely to flutter is its operating incidence; it is not surprising to find that the

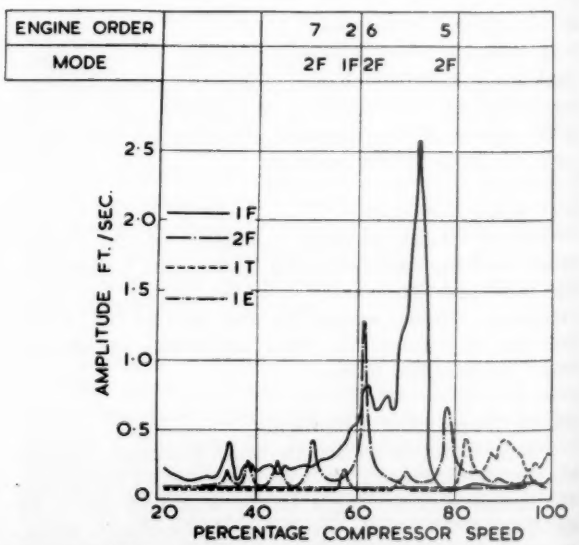


FIGURE 4. Flutter vibration. Amplitude plotted against speed.

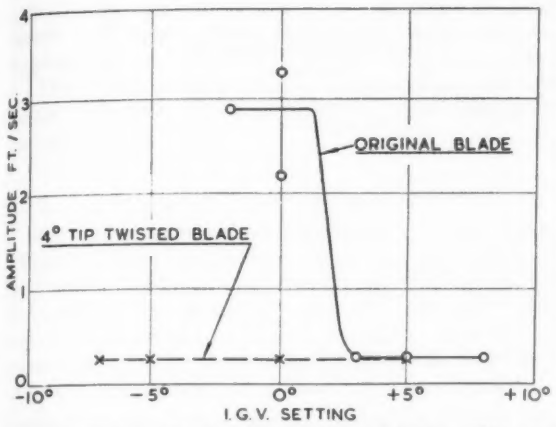


FIGURE 5. Flutter vibration. Amplitude and intake guide vane setting.

amplitude of vibration is very responsive to the inlet guide vane setting. Typical results showing the variation of amplitude with I.G.V. setting are given in Fig. 5. This characteristic of flutter is a useful development test to identify the vibration and indicates the possibility of a satisfactory solution.

4.2.3. *Rotor Blade Twist*

In obtaining a flutter-free compressor by means of I.G.V. setting, some loss of performance is involved unless the complication and weight penalty of variable I.G.V.'s is accepted. Inasmuch as the elimination of the flutter has been achieved by change of rotor incidence conditions, it follows that alteration to the rotor twist should offer a similar benefit. Since flutter vibration occurs in either the fundamental flexure or torsional modes the most responsive section is that at the blade tip. A change in rotor tip stagger does, in fact, control the vibration in either mode and experience shows that performance penalties are less severe.

4.2.4. *Running Line and Nozzle Size*

In a compressor subject to flutter, there is an area of the compressor characteristic over which the vibration may occur. On the test bed with a fixed nozzle, the engine working line may not pass through this zone. However, by the use of nozzles of varying size, the limits of the zone may be located. This is particularly necessary in anticipating the results of flight experience where the running line will move on the compressor characteristic as a consequence of altitude effects on engine performance. The results of an investigation of this type are shown in Fig. 6. By the use of large nozzles, a flutter zone was shown to exist on test bed running which corresponds to flying above the maximum flight altitude.

The presence of a flutter condition in flight can only be accurately established by flight strain gauging, as ground testing cannot be guaranteed to reproduce correctly all the conditions, *e.g.* pressure, temperature, intake and aircraft attitude, which can affect the vibration.

4.2.5. *Change of Material*

A number of tests have been made in which the blade material has been varied. In the majority, the comparison is based on strain gauge tests of blades to

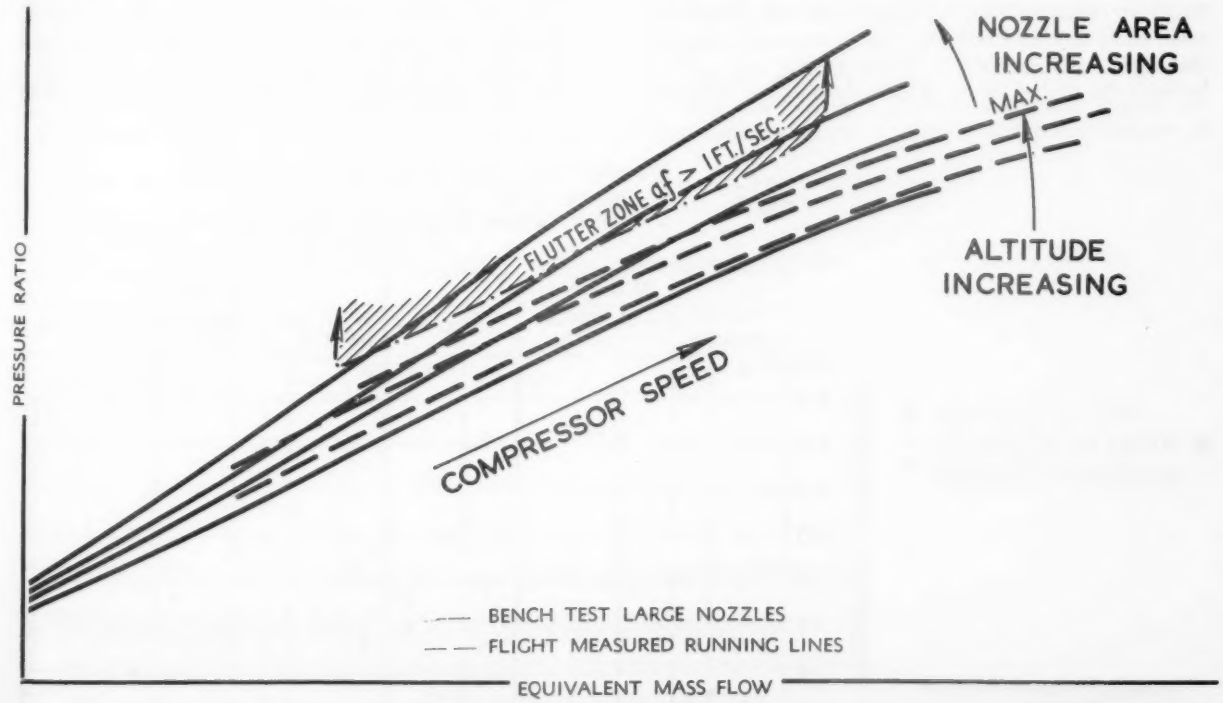


FIGURE 6. Effect of running line on flutter.

TABLE I

Engine Type	*Test Condition*	*Mode*	*Per Cent Design Speed*	*Largest Amplitude Measured (ft./sec.)*		
				Aluminium	*Titanium*	*Steel*
A II	high altitude 30,000 to 50,000 ft.	1*F*	68	3·0	—	3·0
A III	low level, high forward speed	1*F*	68	1·1	—	1·6
B	low level, high forward speed	1*F*	75	4·5	—	0·4
C	test bed design	1*T*	80	6·0	6·0	1·0*

*Modification of blade design below platform compared with aluminium and titanium.

the same physical shape but of changed material mounted in discs of similar material; *e.g.* steel blades —steel disc. Each type of engine was built to as near as possible the same standard.

Certainly from the five examples shown in Table I it cannot be argued that a change of material offers any assurance to reducing flutter amplitudes of vibration.

4.2.6. *Frequency Parameter and Wide Chord Blades*

The tip twisting of engine blades to remove a flutter vibration results in a loss of performance and to overcome this disadvantage a distinguishing design factor between satisfactory and unsatisfactory blades was sought. In Figs. 7 and 8 are presented the experience in both the torsional and flexural modes on a basis of frequency parameter as suggested by Shannon[1]. The blade material has been considered as a variable and a distinction has been made between amplitudes due to flutter or rotating stall. Included are the results of some early tests in which the type of excitation was not identified with certainty. These results are plotted between the dashed lines. Where satisfactory operation has been achieved by tip twisting or I.G.V. settings away from the design, then the cases are indicated by means of open blocks. By the definition of the frequency parameter as used, it remains unaffected by change of tip stagger. In order that the blade may qualify as a satisfactory one, the amplitude of vibration has to be no more than 1·0 ft./sec.

From a consideration of the flexural mode results a frequency parameter band of between 0·27 and 0·33 separates the "satisfactory" blades from those which fluttered. The lower values of the satisfactory blades which are included in this band are blades which were subjected to low amplitudes caused by rotating stall cells.

In the case of the torsional mode a frequency parameter of 1·6 separates, with the one exception of a steel blade, the satisfactory blades from those which vibrate.

In one instance where a large torsional vibration occurred, the blade was redesigned so that its frequency parameter would be comparable with the safe blades. This was achieved by a 40 per cent increase of chord

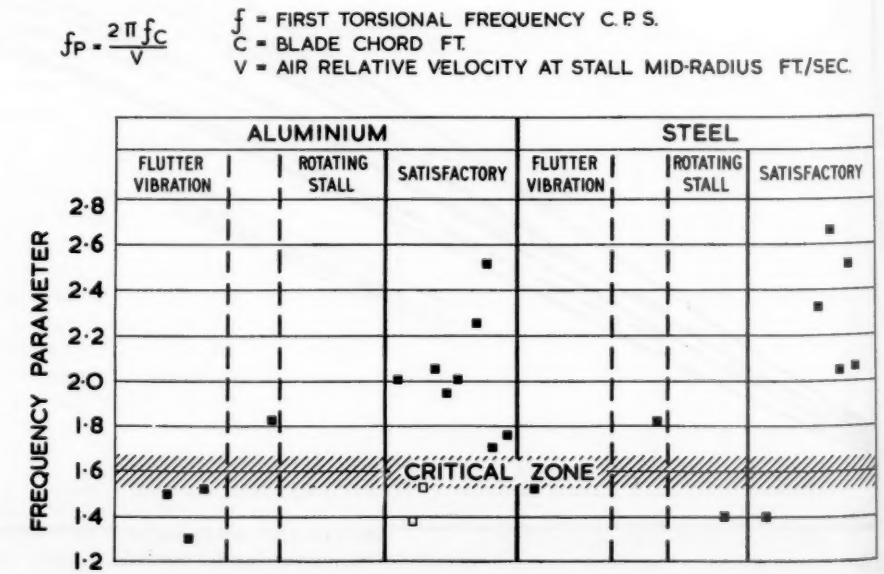


FIGURE 7. Torsional frequency parameter.

and keeping the non-dimensional aerodynamic parameters constant. This successfully eliminates the torsional flutter.

Thus there is experimental evidence to indicate that flutter vibration is influenced by the frequency parameter.

4.2.7. *Correlation of Experience with Theory*

Pearson[2] suggested a mechanism for stall flutter vibration and his analysis neglects the effect of mechanical damping, thus predicting that the amplitude will be independent of blade material. The experimental results quoted in Pearson's paper are in agreement with the recent experience given in Table I showing that material does not affect the amplitude. Pearson's analysis has been extended by Sisto[3] and Carter and Kilpatrick[4] to introduce the effects of mechanical damping. These analyses may be interpreted in terms of a critical flutter velocity or, as Schnittger[5] points out, Carter's expression for critical velocity is equivalent to one of frequency parameter, the value being proportional to the ratio of air to material density and inversely proportional to mechanical damping present. Sisto's expression for the amplitude of vibration also includes terms depending upon the mass ratio, the frequency parameter and the mechanical damping. An attempt was made to correlate our engine experience with Carter's design rule. This was unsuccessful and it is suggested that the validity of expressing the mechanical energy loss solely in terms of the mass of the blade and the logarithmic decrement is questionable.

Shannon and Schnittger had found some correlation of flutter with frequency parameter. The critical figure for torsion which Shannon proposed, *i.e.* 1·5, is very near to the present experimental value of 1·6. In flexure Schnittger suggests the critical value may be between 0·4 and 0·7, which is rather higher than the 0·30 obtained from our engine experience. Carter and Pearson report that there was no correlation of their results on a basis of frequency parameter.

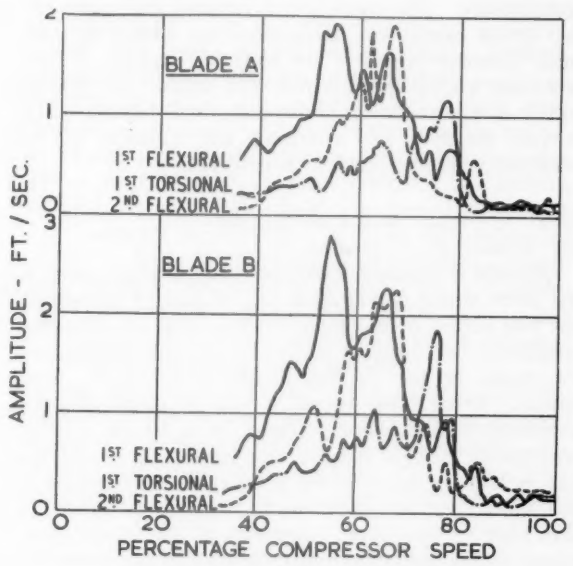


FIGURE 9. Unsteady stall cell excitation.

The mechanism by which tip twisting satisfactorily eliminates flutter throughout the speed range is not fully understood. One would anticipate that the critical incidence would be encountered lower down the speed range. The significance may therefore lie in that the incident velocity at this new condition may be below a critical value. An alternative explanation may be that, by changing the relation of the stall conditions of the various blade sections, the total aerodynamic damping is increased.

4.3. STALL CELL EXCITATION

Stall cell excitation of rotor and stator blades has been experienced on a number of modern designs of

$$f_P = \frac{2\pi f C}{V}$$

f = FIRST FLEXURAL FREQUENCY C.P.S.
C = BLADE CHORD FT.
V = AIR RELATIVE VELOCITY AT STALL MID-RADIUS FT/SEC.

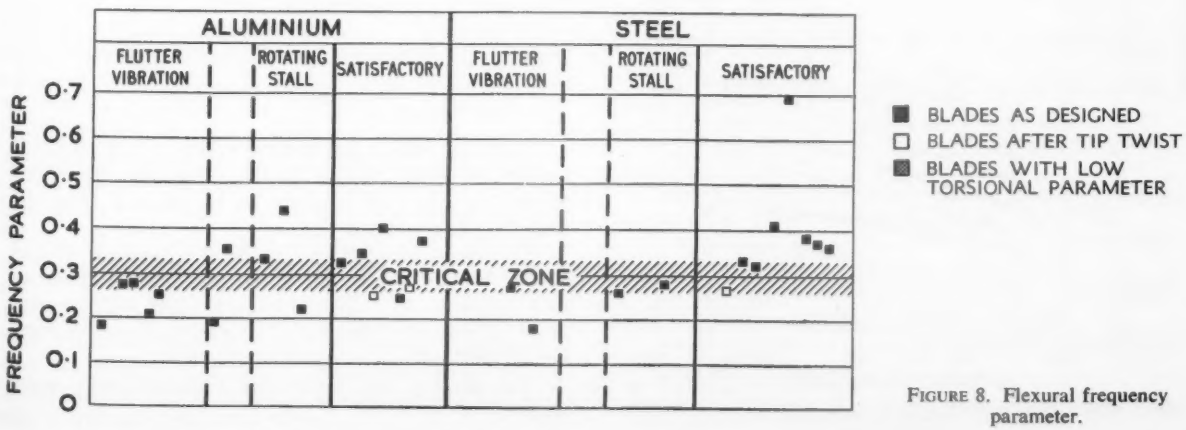


FIGURE 8. Flexural frequency parameter.

compressors. The character of rotating stall falls into two broad categories. Experience has shown that the most common is where the stall cell pattern at any particular engine speed is not very stable. In contrast to this it is possible to obtain a stall cell pattern which is very steady. The character and solution of the resultant vibration problem is different.

4.3.1. *Unsteady Stall Cell Pattern*

(*a*) *Character of Vibration*

Typical amplitude variations with engine speed in the three modes of vibration 1*F*, 2*F* and 1*T* are shown for two blades of the same rotor in Fig. 9. The two amplitude distributions are only roughly similar, *i.e.* the peaks of the various modes occur at the same speeds. From these curves it will be noted that the excitation is non-existent above about 80 per cent of compressor design speed. The rugged nature of the curves and the fact that all three modes are excited at the same time are found to be very characteristic of this form of excitation. Analysis of the strain gauge signal at any particular speed shows that the amplitude of each mode fluctuates rapidly with time. The amplitudes plotted are maximum values.

(*b*) *Identification of Pattern*

If hot wire anemometers are inserted into the compressor, it is found that the signals are not of a steady periodic nature. This fluctuation in signal does not allow the number of stall cells and their speed of rotation to be determined by the classical method of measuring the time for a particular cell to pass between two hot wire anemometers. However, by developing an

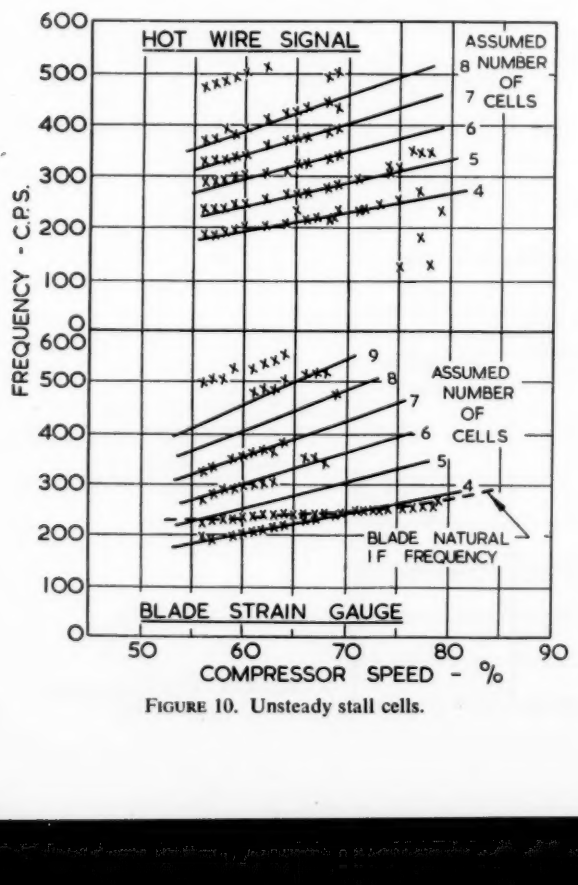


FIGURE 10. Unsteady stall cells.

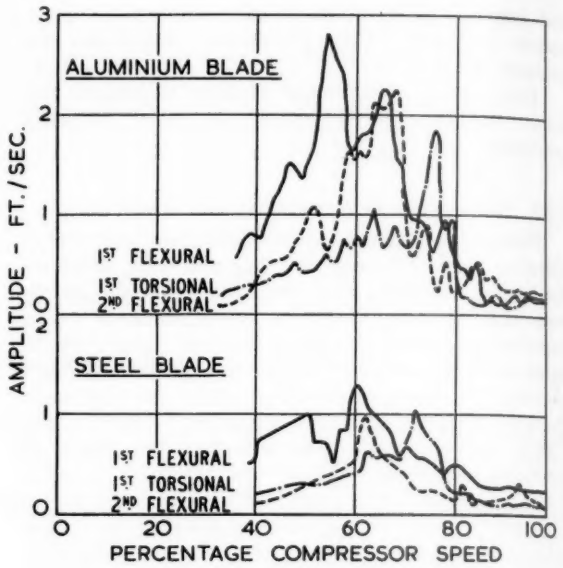


FIGURE 11. Unsteady stall cell excitation.

analysis technique used by N.G.T.E., it is possible to derive the cell pattern. By recording the rotor strain gauge and hot wire anemometer signals on magnetic tape at steady engine conditions then, with the usual electrical wave analyser techniques, the major frequencies can be established. Both the blade and hot wire frequencies form two separate families (Fig. 10), each family consisting of frequencies which form part of an integer series. If it is now assumed, which seems likely, that both sets of frequencies are complementary, it is possible to deduce the pattern. The frequency relative to the stator is given by:

$$f_s = n\alpha N$$

where f_s is frequency relative to stator

n is number of stall cells

αN is the stall cell speed

N is the rotor speed

$$f_r = n(1-\alpha)N$$

where f_r is frequency relative to rotor

therefore $f_s + f_r = nN$.

Thus, by adding the basic frequencies together, the number of stall cells is readily obtained. This then allows the speed of rotation to be derived from the foregoing expressions.

The speed of rotation usually lies between 45 and 55 per cent of the engine speed and usually increases with nearness to compressor surge line and towards lower compressor speeds. The variation in the number of cells occurs in a similar manner.

The pattern can be readily observed over many stages.

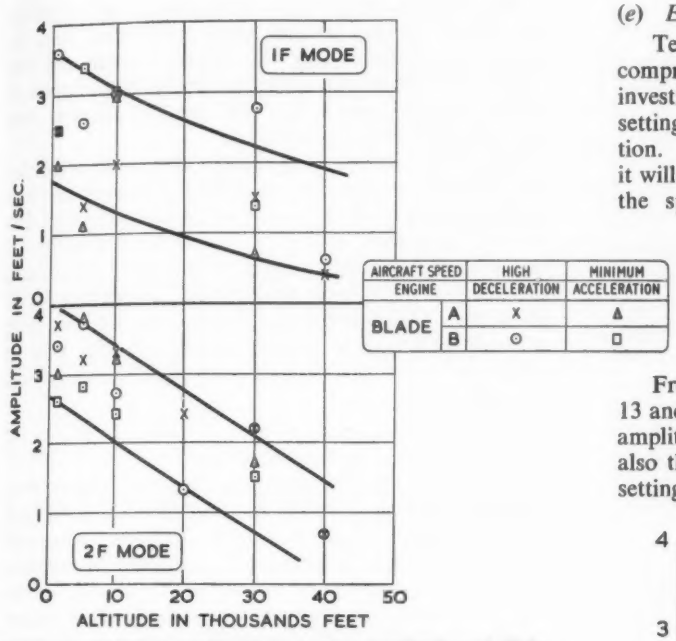


FIGURE 12. Unsteady stall cell excitation amplitude and flight conditions.

(c) *Effect of Change of Material*

If an aluminium blade is replaced with a steel blade of the same shape, then the amplitudes are reduced. This is illustrated in Fig. 11, where aluminium and steel blade amplitudes are compared. They have the same general shape with peak values of the three modes occurring in approximately the same speeds. This reduction, based on a comparison of a number of blades between the number of engine builds, is of the order of two. The most likely reason for the reduction is a combination of the increased mechanical damping with the steel blade and the influence of the increased Young's modulus of the steel. The change in stiffness is significant because the vibration is not strictly of the resonant type.

(d) *Variation of Amplitude with Altitude*

By carrying out flight strain gauge tests it is possible to establish how the peak amplitudes in the various modes are affected by flight conditions. The results of such tests on aluminium first stage rotor blades are given in Fig. 12. While there is a fairly large scatter in the amplitudes of vibration for similar test conditions, it can be seen that there is a general reduction in amplitude with altitude. Included in this figure are results at high and low aircraft speeds with different engine operation and this may account for some of the scatter present. As the stall pattern is irregular, the frequency spectrum of excitation is broad compared with the shift incurred with changed $N/\sqrt{T}$ conditions. The reduction in amplitude with altitude is therefore more consistent with the theory that the vibration is influenced either by mechanical damping or blade stiffness, since the aerodynamic force acting on the rotor blade will be reduced with altitude.

(e) *Effect of Inlet Guide Vane Settings*

Tests have been carried out on both a research compressor (Fig. 13) and the corresponding engine to investigate the effect of varying the inlet guide vane setting on the stall cell pattern and the resulting excitation. From the stall cell patterns on the characteristics it will be seen that with the more positive I.G.V. setting the speed at which the stall cells are eliminated is reduced significantly. Also, at the more positive settings and at a particular speed, a bigger range in the number of stall cells is possible. This would indicate that the pattern is less stable and hence a reduction in blade vibration amplitude would be expected.

From the results of engine strain gauge tests (Figs. 13 and 14), it will be seen that the speed range of large amplitudes is reduced with positive I.G.V. setting and also that there is a slight reduction in amplitude with settings up to $+22°$. The reduction is larger at $+29°$.

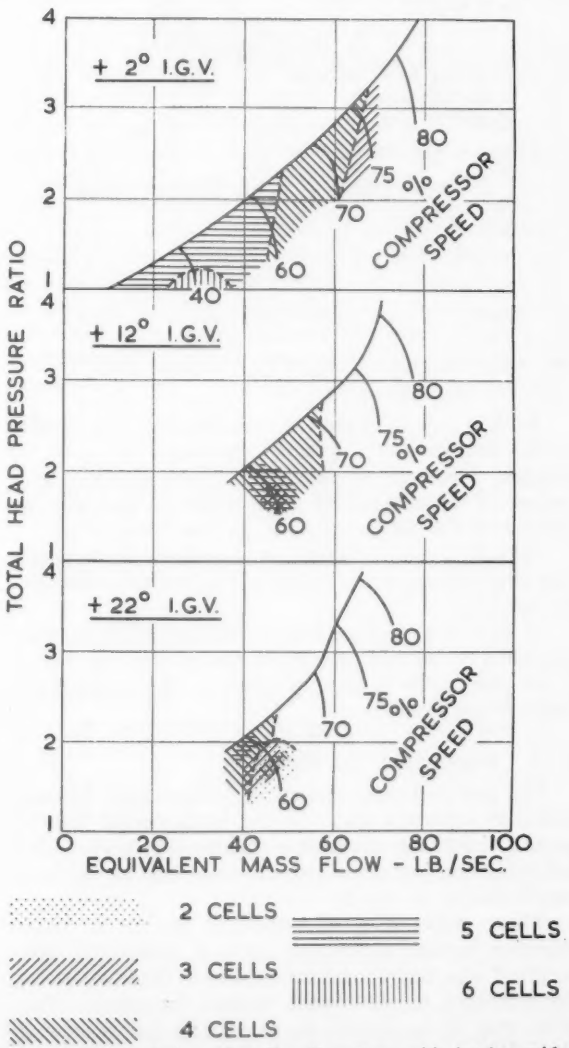


FIGURE 13. Variation of stall cell pattern with intake guide vane setting.

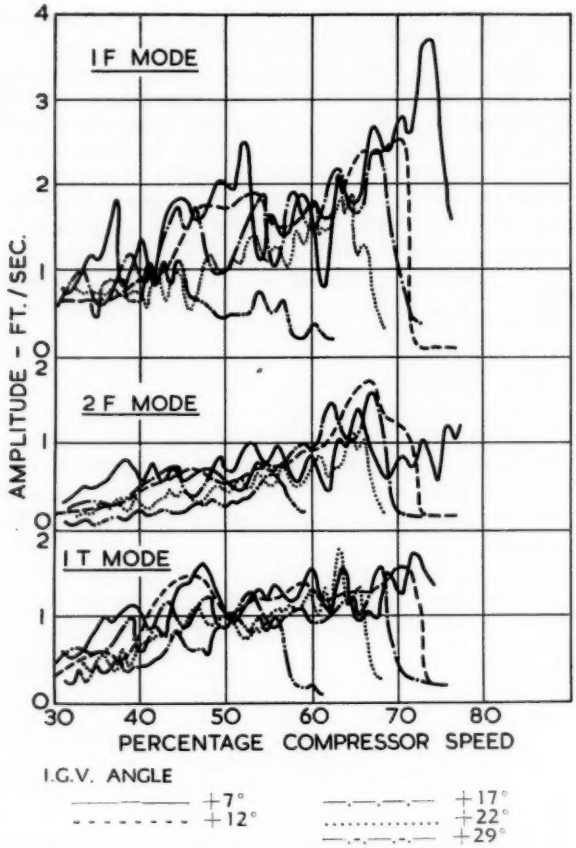


FIGURE 14. Amplitude at intake guide vane settings.

(f) Other Variables—Tip Twist, Nozzle Area, Blade Frequency

In the case of flutter, the amplitudes were significantly changed with a small alteration in blade tip stagger. However, in the case of blades operating in a region of unsteady stall cells, there is generally no significant alteration of amplitude with blade twist.

Similarly, the variation in amplitude with nozzle size when blades are being excited by rotating stall cells is negligible.

It can be appreciated from the plot of frequencies measured on the hot wire anemometers (Fig. 10), that it is not practicable to alter the blade so that a particular mode is not excited.

4.3.2. *Steady Stall Cell Pattern*

On one particular design of compressor, isolated peaks of vibration occur in the fundamental flexural mode. Unlike the vibration in the unsteady type of stall cell excitation just discussed, the amplitude at the peak was found to be steady.

These peaks were identified to be not a flutter vibration because the engine speed at which the peak occurred was slightly different for each blade reflecting the difference in the blade's natural frequency. This effect may be confirmed by examining the change of phase between the blades with engine speed.

By the use of hot wire anemometers in the casing, the details of the pattern were established and the results are plotted in Fig. 15. In this case the hot wire signals were so steady and clear that it was possible to deduce the number of cells and speed of rotation from the observations of two probes.

Since the pattern is so regular, it is anticipated that the amplitudes could be reduced to an acceptable level by choosing a blade frequency to avoid resonances with the stall cell basic pattern. This is confirmed by the fact that the adjacent stage with increased frequencies did not vibrate at large amplitudes. Further, it is implied that changes to mechanical damping and blade stiffness will have a smaller effect with this type of excitation than that found with the unsteady stall pattern.

4.3.3. *Further Considerations*

Experience to date has not suggested, apart from variable I.G.V.'s, any sure method of eliminating stall cell excitation. A survey of the various compressor designs does not indicate any particular controlling feature. There are some indications that blade section efficiency of the stage where the rotating stall originates may be significant. Further, perhaps there is a correlation with stage work and/or overall pressure ratio.

A considerable amount of investigation has been carried out in research establishments into the effects on stall cell pattern of inlet baffles, ramps, air injection, blade stage spacing and aspect ratio. While none of these provide a satisfactory engine design solution, within the content of some of these approaches may lie a future solution.

4.4. RANDOM TYPE OF EXCITATION

4.4.1. *Character of Vibration*

In one particular series of engine designs the early stage aluminium blades suffered, over a fairly large

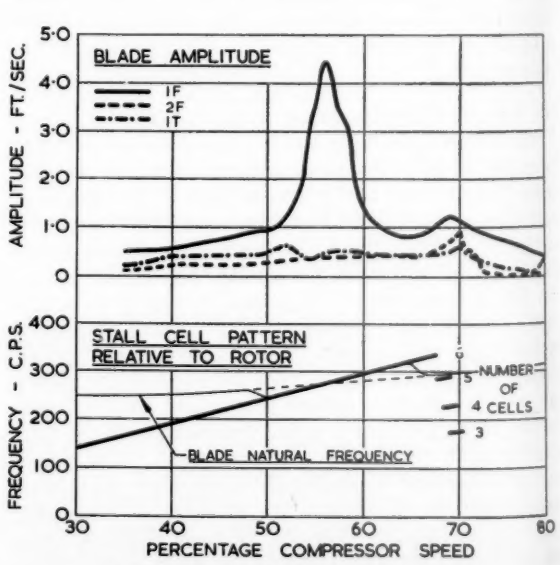


FIGURE 15. Steady stall cell excitation.

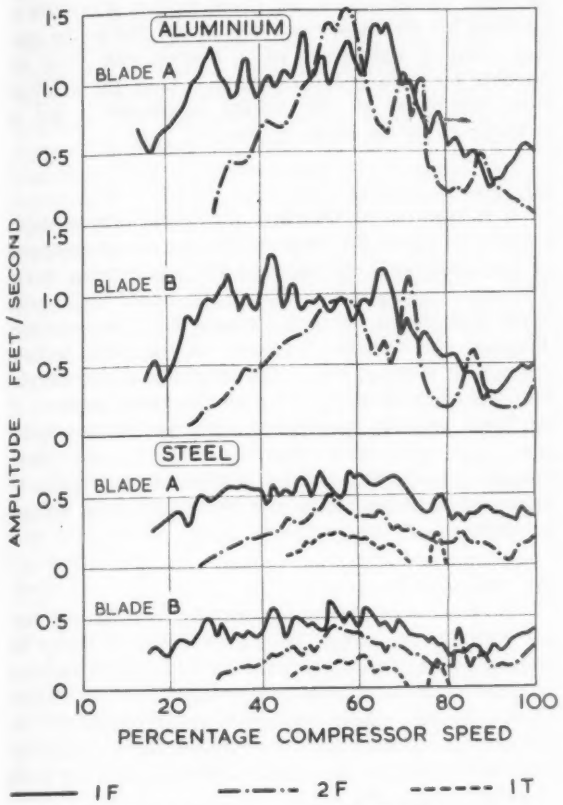


FIGURE 16. Random amplitude vibration.

portion of the speed range, from large amplitudes in both the first and second flexural modes. Typical curves of amplitude plotted against speed are shown in Fig. 16. In all cases of engines tested there was little amplitude in the torsional modes. On detailed examination of the vibration it was found that the amplitude fluctuated rapidly with time and each blade vibrated at its own natural frequency. The amplitude distribution of the strain gauge signal had the character of filtered random noise. Hot wire anemometers, together with pressure pick-ups, were used to establish the type of air flow present. From these results there was no evidence of a stall cell pattern.

4.4.2. *Effect of Aerodynamic Changes to Blade*

It was established that neither positive nor negative I.G.V. settings significantly altered the amplitude pattern. Similarly, no effect was obtained from a blade tip twist change nor with a nozzle change.

4.4.3. *Change of Amplitude with Flight Condition*

The results of flight tests show that the amplitude varied fairly proportionally with intake pressure. The results are given in Fig. 17.

4.4.4. *Mechanical Detail of Root Fixing*

In the particular design of compressor under investigation, the clamping loads of the compressor are taken through the blade root platforms. The amplitude of vibration was significantly affected by the magnitude of the resulting clamping force on the blades. This presumably altered the mechanical damping present as the lower loading would allow slight relative movement of the blade platform causing fretting and energy loss. Further, by altering the root design from a two to three lobe root, the amplitudes were increased.

From this evidence it is deduced that the mechanical damping significantly controls the amplitude of vibration. This hypothesis is also reinforced by the variation of amplitude with altitude shown earlier.

4.4.5. *Change of Material*

By changing the blade material from aluminium to steel, a reduction in amplitude of about 3 to 1 was obtained (Fig. 16). The reason for this reduction may be associated with an increased mechanical damping of the steel blade compared to aluminium. The experimental determination of the mechanical damping associated with the fir-tree root of aluminium and steel blading is not very readily obtained. Some preliminary rig tests which have been carried out indicated that the damping in the steel blade is greater than that of the aluminium. A second reason for the reduction of amplitude with the steel blading may be due to the increased stiffness of the blade. Thus under the assumed

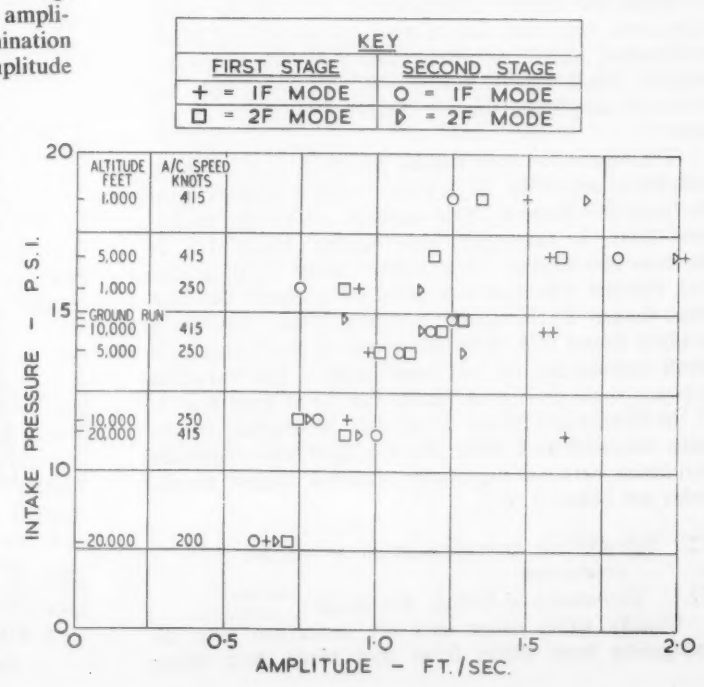


FIGURE 17. Random amplitude vibration variation with intake pressure.

random nature of the excitation, the amplitudes are likely to be reduced inversely as the ratio of the Young's modulus, *i.e.* about 3 to 1.

5. Application of Engine Results to Development

We have so far considered the results of strain gauging a number of engine designs and have studied the type of vibration present. The immediate use of this information is in assisting the engine development. Engine strain gauge testing falls into two broad groups. The first is associated with establishing the cause of failure of a particular blade row. The second group of tests occurs later in the engine life when a survey is carried out aimed at deciding whether an engine under operating conditions is liable to failure. In both these investigations it is necessary to estimate the seriousness of the vibration observed in terms of engine life. Often short term failures on the test bed occur due to fairly large amplitudes and it is easy to show that the measured amplitude could account for the failure.

However, with the longer term failures and also on an engine survey when the amplitudes are moderate, the estimation of fatigue life is very difficult. It will be of interest to consider some of the problems which arise.

5.1. AMPLITUDE OF VIBRATION

There are three obvious factors which affect the significance of a strain gauge test:—

(*i*) the accuracy of measuring the amplitude of vibration,

(*ii*) the scatter in amplitude between blades in a stage,

(*iii*) the scatter in amplitude between engines of the same build standard.

From the known accuracies of each of the many operations connected with a strain gauge test, *e.g.* blade calibration, signal recording and playback, measurement of amplitude of mode, it is considered that the vibration amplitude can be measured to about 20 per cent.

The scatter between blades, however, is much more difficult to establish. To a large extent it depends upon the type of vibration. For instance, with wake excitation there is relatively little scatter (ratio 1·5 : 1) between two blades. The scatter under rotating stall and random vibration can often be between two and three times. In the case of a strong flutter vibration it is often found that there are zones of both large and small amplitudes on the same stage. The variation between these groups of blades can be at least 6 to 1.

In most cases where a number of engines to the same standard have been strain gauged, the amplitude variations between the blades showing largest amplitudes are below 2 to 1.

5.2. THEORETICAL DETERMINATION OF FAILING CONDITION

5.2.1. *Estimation of Failing Amplitude*

Usually strain gauge tests are concerned with investigating both blade form and blade root fixing failures. In the case of the blade form it is possible to estimate the steady stresses acting, but due to the complex loading conditions of a fir-tree root, it is not possible to form a life estimate. Thus for a fir-tree root, prediction of the failing amplitude is not as possible as for the blade profile.

(a) Steady Stresses

It is possible to calculate the local nominal steady stresses acting on the blade section which are composed of the centrifugal stresses and the gas bending stress. The centrifugal stress is due to the radial load on the blade and also a bending moment if, as is sometimes designed, the centres of gravity of the outer sections are not on a radial line. The accuracy of this calculation will depend upon the manufacturing accuracy of the blade and the assumption made in determining the gas loads and their distribution along the blade. Possibly, until the steady stresses can actually be measured experimentally, the errors involved will not be known.

(b) Material Properties

In the case of materials normally used for compressor blading, the slopes of the stress-log N curves for stresses above the fatigue limit are such that a variation of approximately 20 per cent is equivalent to a factor of ten in life. This variation in life illustrates the seriousness of inaccuracies of amplitude measurement and the scatter between blades and engines, when trying to predict blade life.

When combined fatigue stress data is not available from laboratory testing, use has to be made of the "safe" approximation of adopting a straight line Goodman Diagram between the stress to rupture strength and an endurance fatigue amplitude. This endurance amplitude is deduced from the results of rig fatigue tests on the type of blade in the correct mode of vibration.

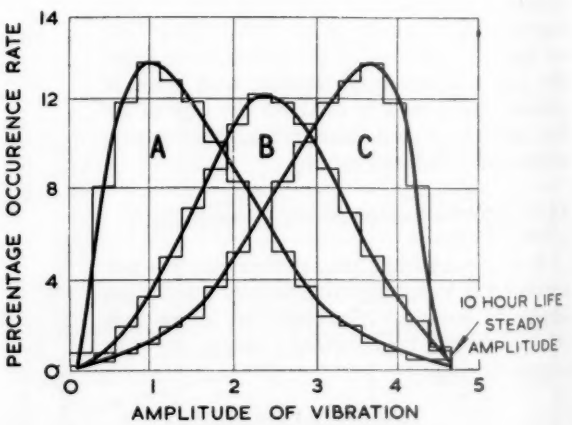


FIGURE 18. Effect of amplitude distribution on life.

(*c*) *Amplitude Variation*

In the majority of cases of serious vibration, the amplitude fluctuates with time. The character of the amplitude distribution will have a serious effect on the failing amplitude when expressed as the maximum peak amplitude. In Fig. 18 are drawn three representative types of amplitude distributions. The life for each distribution has been calculated by the use of Miner's hypothesis[6]. Taking the life at the common maximum amplitude as ten hours, the failure times for the three distributions become 1050, 304 and 112 hours.

It is thus necessary to obtain some indication of the amplitude distribution in order to assign the correct seriousness to two vibrations of equal peak amplitude.

(*d*) *Presence of More Than One Mode*

As has been shown, it is possible for a blade to vibrate at comparably serious amplitudes in more than one mode of vibration. So far it is not possible to calculate the effect of the additional modes, as this will depend upon the detail stress distribution of each mode. The reduction in failing amplitude has been verified by rig fatigue tests in two modes at once on one type of blade.

(*e*) *Knowledge of Flight History*

An attempt to calculate blade life which allows for variation of amplitude with engine speed and flight condition requires an exact knowledge of the engine operation. This information, to the accuracy necessary, is not normally available until the engine and aircraft have flown.

5.2.2. *Consideration of Theoretical Estimate*

By consideration of all factors dealt with in the previous sections, it is not surprising that in some cases the estimated failing amplitudes are in error by a factor of two. This, of course, corresponds to a life factor of about 5,000. It is thus not possible to rely on calculations alone to indicate the satisfactory nature of a particular blade vibration.

The only alternative is the use of special engine development testing.

5.2.3. *Development Engine Tests*

(*a*) *Endurance Tests*

On completion of bench and flight strain gauge tests, a knowledge will be obtained of the variation with engine speed of the maximum amplitudes obtained under all conditions. Thus by estimating the time likely to be spent in a particular speed range, the details of an endurance test can be established.

By the use of strain gauges on the endurance test engine, it is possible to ensure that the correct amplitudes and character of vibration required to simulate the conditions are obtained. The amplitudes are usually increased by the use of intake spoilers, I.G.V. settings, or nozzle size changes. By the operation of a motorised throttle lever, the engine speed is slowly varied over the speed range under test. A number of these test cycles are recorded and analysed to confirm the test conditions.

This type of testing can be used for vibration due to wakes, rotating stall cells or random excitation. Because of the nature of flutter, its presence in an engine cannot be tolerated and a means of ensuring that the engine is flutter-free must be found.

(*b*) *Determining Flutter Margins*

In the case of a flutter type of vibration where the amplitude is likely to reach short term failing amplitudes due to small changes in engine condition, it is necessary to ensure that an engine type has a sufficient margin of safety from the critical condition.

Since flutter is primarily dependent upon the blade incidence and running line, the most likely causes of variation between engines are manufacturing settings of blade angles, performance variations causing running line changes, deterioration of performance due to compressor fouling, and the effects of de-icing air leaks and bleeds. Thus by varying the I.G.V. setting to increase the incidence on the first row of blades, it is possible to indicate the available margin to accommodate these contingencies. By the use of large nozzles it is possible to move the running line and so indicate the allowable safe movement of the running line due to flying conditions or fouling of the compressor.

5.2.4. *Material Change to Overcome Blade Failure*

It is usual for compressor blades to be made from aluminium, steel or titanium. When a blade fails in service or on development, one of the first aspects of redesign is a review of the available materials. From a knowledge of the type of vibration causing failure, the effectiveness of a change in material, fatigue properties and the steady stressing conditions, can be assessed.

From the experience covered earlier it has been shown that vibration falls into two classes:—

(*a*) those where material does not influence the amplitude,

(*b*) those where the amplitude is inversely proportional to the Young's modulus or density of the material.

A theoretical comparison has been made of the capacity of blades of the three materials to withstand excitation of these two categories. The capacity is expressed in terms of the change in the excitation causing failure of a steel blade. Where material influences the amplitudes of vibration it is found that the aluminium blade will only withstand 0·23 of the excitation of the steel blade, whereas the titanium will withstand 1·15. These calculations have been based upon a nominal steel design with a centrifugal stress of 10 tons/in.^{2} and a gas bending stress of 5 tons/in.^{2} The material properties used are shown in Table II.

With the type of vibration which is unaffected by material properties, the variation in excitation which

TABLE II

Material	*U.T.S.* tons/in.^{2}	*Failing Amplitude* ft./sec.
Aluminium	22	5·5
Titanium	68	11·0
Steel	65	6·5

can be withstood by an aluminium blade is only 0·64, while the titanium blade can withstand 1·86 of the excitation on a steel blade.

6. Design Rules for Blade Vibration

Apart from wake excitation the knowledge of the factors controlling blade vibration are not yet sufficiently understood or established to justify the modification of the blade design which would result in prejudicing the engine's performance. Where this possible penalty does not occur the blade may, of course, be modified to comply with the latest design rules. This will enable confidence to be built up in these semi-theoretical rules.

In the case of wake excitation it is found that serious amplitudes are not likely to arise with conventional designs, if the basic resonances of the lowest four modes of vibration, with the main obstructions like intake vanes, are removed from the engine speed range between idling and take-off. This applies to the two stages adjacent to the excitation.

So that the general level of vibration and the lower levels of random type of vibration can be accommodated, the compressor blades should be stressed to withstand a minimum vibration of 2·0 ft./sec.

Where a flutter type of vibration is likely to be encountered, then the frequency parameter rule may be used. However, it must be emphasised that this is strictly an empirical rule which by no means explains all the aspects involved in flutter vibrations and can only be used as an experimental parameter until further confidence or theoretical justification is gained.

It is generally accepted that it is not yet possible to predict whether a compressor is likely to be subject to rotating stall cells. Nor is it possible with any certainty to predict the number of stall cells and their rotational speed. Thus, apart from examining the possibility of a blade resonance with a typical stall cell pattern, little can be done at the design stage to safeguard against this trouble.

ACKNOWLEDGMENTS

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Performance Problems in Large Rocket Engines*

by

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1. Introduction

In the context of this paper, the term "large rocket engines" refers to those liquid propellant engines at present being built for use with ballistic missiles. The engineers concerned with their development however, are always hoping that the same units may be used for launching satellites and for the early stages of space flight.

Now it is axiomatic that in such vehicles the take-off thrust should exceed the weight. On the other hand, common propellant combinations only give an impulse of about 240 pound seconds per pound of propellants. Thus it follows that the duration of one stage of powered flight at constant thrust could not exceed 240 seconds, even if the net take-off acceleration were zero and the whole missile consisted of propellants. Allowing for sensible take-off accelerations, and for the weight of structure, engines and payload, a more realistic figure would be 150 seconds. As re-use of the engine system is not usually contemplated, the entire operational life of a large rocket engine is probably less than three minutes.

There seems little point in delivering payloads of much less than a ton. If we assumed that engines, structure and guidance were all of about the same weight, the empty weight of the missile would then be 4 tons. To achieve a ballistic range of 1,500 miles with a single stage rocket, such as Thor or Jupiter, nearly 90 per cent of the take-off weight must be propellants, so that the total take-off weight would be some 40 tons. Thus one arrives at a round figure of 50 tons or some 110,000 pounds, as a typical thrust level for a "large" rocket engine. In later Sections a hypothetical engine of this size will be taken as an example.

At a specific impulse of 240 lb.sec./lb. this thrust corresponds to a liquid propellant flow of 450 lb./sec. By comparison, the Conway engine at full take-off thrust requires 3·4 lb. liquid fuel per second though this burns with an air flow of nearly 300 lb./sec. The jet velocity would be about 240×32 or 7,500 ft./sec., so that the kinetic energy in the jet of our hypothetical rocket engine represents about $(450 \times 7{,}500^2)/(2 \times 32 \times 550)$ or nearly three quarters of a million horsepower! On the other hand the power required to pump the propellants would only be about 2,000 h.p., which gives a very small ratio of compression to expansion work as compared to an air breathing engine.

One more "order of magnitude" figure could be added. As is well known, the noise produced by a normal turbo-jet engine increases as the eighth power of the jet velocity. Since the power equivalent of the jet increases only as the cube of the velocity, an increasing proportion of the jet power appears as sound when the velocity increases. When the jet velocity becomes highly supersonic, however, the eighth power law is no longer obeyed, and the energy radiated as noise settles out at about one per cent of the kinetic energy in the jet. Thus on our hypothetical engine of 50 tons thrust, the total noise energy radiated by the jet is 7,500 h.p., or over five megawatts. This is nearly ten million times the output of a normal loudspeaker!

2. The Basic Layout

The basic unit of the rocket engine is the thrust chamber, in which pressure is maintained, and propulsive thrust produced, by the continuous combustion of the propellants. If the chamber were cylindrical the gross thrust would equal the product of the injector end pressure and the cross sectional area: however, the thrust is increased by about one half by the pressure inside the diverging nozzle section. The operating pressure is limited by stresses in the chamber and supply lines, and by the complications of pump design, and 500 lb./in.^{2} abs. is typical of current practice. Thus the throat area required by our hypothetical 50 ton thrust engine would be $112{,}000/500 \times 1{\cdot}5 = 150$ in.^{2}, corresponding to 14 in. diameter.

It would not be feasible to supply the propellants from pressurised tanks because of the weight involved. They must therefore be pumped in, the pumps being driven by some form of gas turbine. In many early engines the gases were obtained from a separate supply of hydrogen peroxide, catalytically decomposed to form hot steam and oxygen. A more compact, self-contained, arrangement is to produce the gases in a special "gas generator" by combustion of propellants drawn from the main supply lines. Fig. 1 shows the diagrammatic arrangement of such a system, while an actual engine is shown in Figs. 2 and 3.

3. Propellants

Since the rocket-powered vehicle carries all its propellants with it, it is vitally important to use the minimum total propellant flow ($\dot{M}$) to obtain a given thrust. As the thrust is practically proportional to the product of throat area and chamber pressure ($A \times P$) we require to maximise the fraction $A \times P/\dot{M}$. This fraction,

*Based on a lecture given before the Derby Branch on 2nd February 1959.

Revised 1st January 1960.

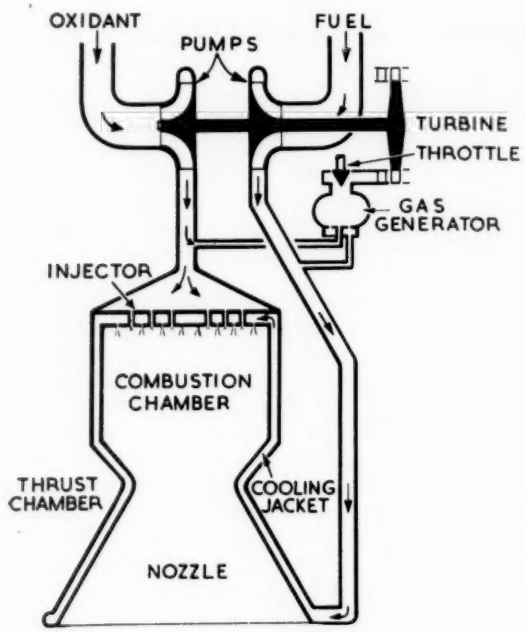

FIGURE 1. Diagrammatic engine layout.

multiplied by the gravitational constant, is known as the characteristic velocity of the propellant mixture.

From the normal laws of gas expansions, the characteristic velocity is approximately proportional to the square root of the total temperature divided by the gas molecular weight, and it is therefore this fraction that must be maximised to obtain the best performance.

Calculations show that of all the readily available propellant combinations, the best performance is obtained with liquid oxygen and a kerosine type fuel. Although the low temperature of the oxygen causes inconveniences, the propellants are cheap and the products non-toxic. Fig. 4 shows the complete curves of temperature, molecular weight and characteristic velocity plotted against mixture ratio for this combination. The continuing decrease of molecular weight on the fuel-rich side of the stoichiometric point tends to counterbalance the fall in temperature, so that the optimum operating mixture is about 30 per cent fuel rich.

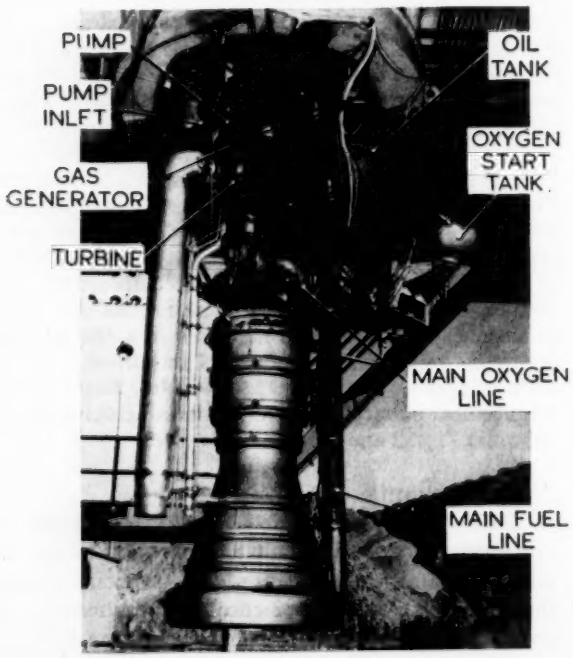

FIGURE 2. Large rocket engine on test stand.

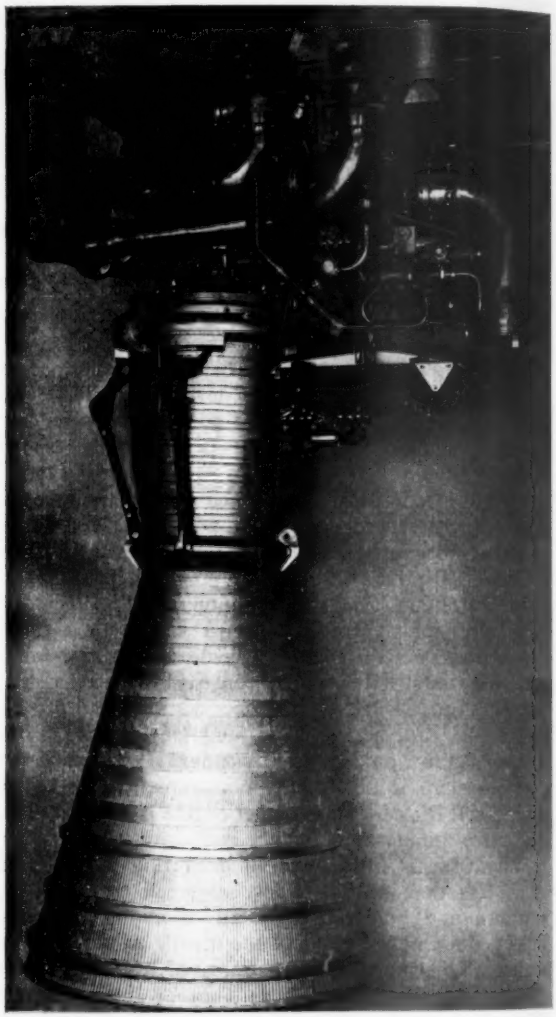

FIGURE 3. Large Rolls-Royce rocket engine.

4. Thrust Chamber Heat Transfer

It will be evident from the foregoing that the best performance is obtained when working temperatures are high, of the order of 3,500°K, which is over 1,000 degrees higher than is achieved in the primary zone of a turbo-jet engine combustion chamber. Cooling of the thrust chamber walls therefore presents a grave problem.

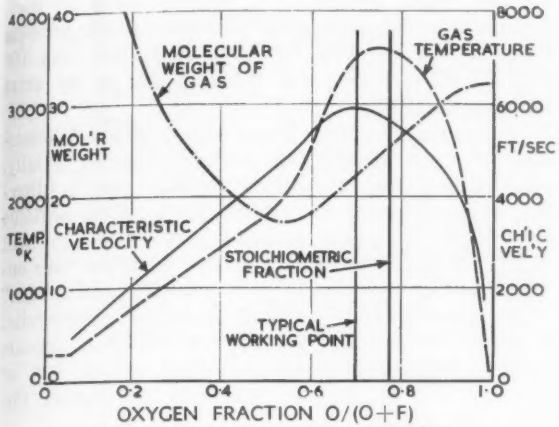

FIGURE 4. Kerosine/oxygen combustion.

In fact, for a typical chamber, the calculated heat transfer rate to the walls at the throat (the worst position) may be of the order of 9 B.Th.u./in.^{2} sec., unless they are allowed to run at temperatures exceeding the melting points of most metals and alloys. By comparison the rate of heat transfer to the flame tube of a typical turbo-jet engine flying at "Farnborough" conditions—high Mach number and low altitude—is only one fifteenth of this value and that to a domestic kettle less again by the same factor (*see* Fig. 5). Regenerative wall cooling, using one of the propellants, is therefore essential in rocket chambers: double wall and tubular methods of chamber construction have both been used.

Of the two propellants available there is usually a greater volume flow of oxidant than of fuel, and oxidant cooling is invariably used in peroxide motors. However, it is sometimes difficult to find wall materials compatible with a hot oxidant and an oxidant leak may present a worse fire hazard than a fuel leak. Also, if liquid oxygen is used as coolant at pressures of the order of 600 lb./in.^{2} abs., boiling at the wall is possible, with the consequent chance of vapour binding and burnout. This cannot occur with a fuel such as kerosine, since this pressure is above the critical value.

On thrust chambers cooled with hydrocarbon fuels it has been found that, when the proportion of fuel near the walls is increased to counteract overheating, the cooling effect observed is much greater than would be expected from simple heat transfer theory. This is because a thin film of soot is deposited on the walls during running if the mixture ratio is rich*. The soot has an exceedingly low conductivity—unlike solid carbon or graphite—and so acts as a thermal insulator: a layer two thousandths of an inch thick can carry a temperature drop of several hundred degrees. (*See* section diagram on Fig. 5.) This protective layer has the enormous advantage that, unlike other refractory coatings, it is self renewing. In fact very sensitive measurements of wall temperatures at North American Aviation have shown a "saw-tooth" variation of temperature with time, the temperature rising momentarily as pieces of the coating flaked off and then falling again as more soot was deposited. Naturally non-carbon-bearing fuels will be at a considerable disadvantage in this respect, and one might expect very high heat transfer rates with some super-fuels.

It may also be observed that since the heat transfer coefficient on both the gas and fuel sides decreases when an engine is throttled, while that of the wall remains constant, the total temperature drop, through wall plus soot, is reduced. Thus throttling would tend to *increase* the metal temperatures. This effect may be slightly offset by the reduced radiation at lower pressures although the heat transferred by radiation is normally assumed to be very much lower than that by convection.

5. Combustion Inefficiency

This fuel-rich layer at the walls, introduced for cooling purposes, may also hold the key to the apparent combustion inefficiency of rocket engines. Those who work on air breathing engines, where one can get 99 per cent combustion efficiency at low pressure and low temperatures, with oxygen diluted by four parts of nitrogen, may find it hard to imagine that rocket engine combustion could be other than 100 per cent efficient. However, it is a sad fact that the specific impulse values measured on the test bed are sometimes as much as 5 per cent short of the ideal value. Most of the deficiency is in the characteristic velocity, and, remembering that this depends on the *square root* of the temperature, suggests a combustion efficiency that is pretty poor by gas turbine standards.

Now at the high temperature in the combustion chamber the combustion products tend to dissociate. As the gases expand to lower temperatures, however, the

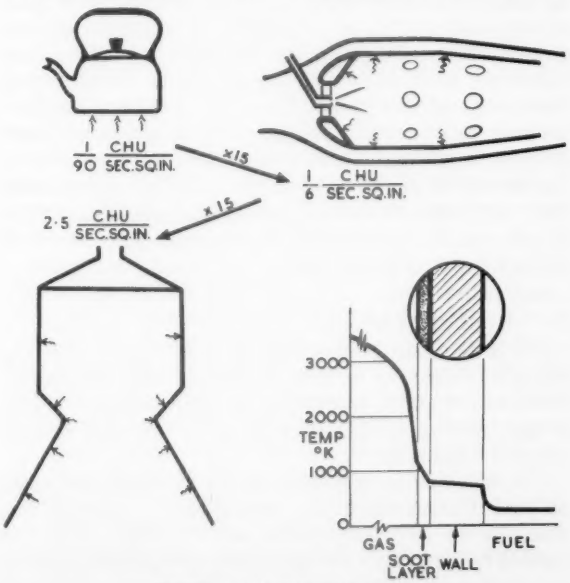

FIGURE 5. Heat transfer rates.

*This effect has recently been discussed in a Lecture to the Royal Aeronautical Society by Professor D. B. Spalding, entitled "Heat and Mass Transfer in Aeronautical Engineering" on 24th Nov. 1959, *Aeronautical Quarterly, May* 1960.

dissociated species, such as atomic oxygen and hydrogen and OH groups, are assumed to recombine, releasing energy and producing a sort of reheat effect. If the expansion time were so short that this recombination did not occur, we would expect a lower specific impulse to be recorded, and this excuse (expansion at "frozen" composition) is sometimes offered as an explanation of the low apparent combustion efficiency. However, there seems little doubt that recombination must occur in the nozzle; anyone who has tried to capture an oxygen atom in a sampling probe knows how quickly it recombines. (Recombination of the other constituents, as for example in the water gas reaction involving CO, CO_2, H_2, and H_2O, is slow, but as no appreciable energy is liberated by this reaction it does not affect the issue.) It might be argued that the energy of recombination is not immediately transferred from vibrational to translational modes and so is not made available. However, an analysis of the heat release rates required to maintain a state very close to equilibrium show them to be comparable to those currently obtained in gas turbine combustion chambers. Furthermore the specific impulse measured with some propellant combinations is greater than the value that would be expected on the basis of expansion at "frozen" composition.

It does not therefore appear likely that continued dissociation is responsible for combustion inefficiency.

By similar arguments it appears probable that reaction has locally proceeded to completion everywhere in the chamber before the products reach the nozzle.

It can easily be understood that if one is working at the peak of the curve of characteristic velocity or specific impulse versus mixture ratio, any variation of mixture ratio must impair the performance. A possible cause of the apparent combustion inefficiency is thus inhomogeneity in the exhaust, either from point to point, or from time to time at one point. The fuel rich mixture at the walls is one obvious source of this type of loss. It is here that one major difference between rocket and turbo-jet combustion appears—in the primary zone of a turbo-jet the gases are stirred and mixed by a pressure drop equivalent to some twenty times the outlet dynamic head—in a rocket chamber there is a continually falling pressure gradient which tends to suppress even the turbulence produced initially by the action of the injector jets. In fact experiments have confirmed that radial mixing is negligible, a speck of salt on the injector face producing a thin streak of sodium flame in the exhaust.

6. Injector Design

It is therefore evident that the prime purpose of the injector should be to mix the propellants thoroughly. However, of all the techniques involved in rocket engine design, that of producing a successful injector savours most of a black art.

It must first be remembered that the flows are huge, so that if atomisation and mixing are to be good vast numbers of injection points are required. This has tended rather to rule out the more sophisticated types of injectors such as the swirl atomisers used on turbo-jet engines, so that comparatively simple orifices are used. It must also be remembered that the available pressure drops cannot be made too large (say more than 100 lb./in.^{2}) without incurring penalties due to the extra pumping involved.

In general it has been found that the simple "showerhead" injection pattern (all orifices discharging axially) gives poor mixing; the "like-on-unlike" pattern (directing one propellant at another) tends to be unstable since the overall mixing pattern is very sensitive to small changes in the surrounding gas flow; while the "like-on-like" injection pair system gives a readily mixing "fan" of propellant droplets that is an acceptable compromise. However, no efficient injector yet designed appears immune from combustion instability of one sort or another, and it is here necessary to discuss this fascinating subject.

7. Combustion Instability

There are two main types of combustion instability, low frequency and high frequency.

Low frequency instability, or "chugging," is caused by the finite time, or "combustion delay," which elapses between the injection of propellants and their combustion. This delay is associated with the time necessary for atomisation, vaporisation and ignition. Suppose now that for some reason the chamber pressure, P_c, starts to oscillate, following the sinusoidal line on Fig. 6. The rate at which gas flows out of the chamber will then fluctuate in phase with the chamber pressure. Since the propellant inflow depends on the difference between the applied injection pressure, P_i, which can be supposed constant in a simple analysis, and the chamber pressure, it will oscillate, too, but 180 degrees out of phase. The rate at which the propellants *burn*, however, will be out of phase with the injection rate by an amount corresponding to the combustion delay time. If now the delay time is somewhere between a quarter and a half cycle of the oscillation, then the quantity of gas in the chamber (which is the integrated difference between the rate of burning and the outflow), will oscillate in phase with the pressure fluctuations and tend to reinforce them.

The relative magnitudes of pressure and mass flow oscillations, which determine whether the oscillation will then be self sustaining, are determined by the ratio of injection pressure drop to chamber pressure and by the capacity of the chamber. Now if, for example, $P_c = 500$ lb./in.^{2} abs. and $P_i - P_c = 100$ lb./in.^{2}, a one per cent variation in chamber pressure will cause a $2\frac{1}{2}$ per cent fluctuation in mass flow. On the other hand, if the same chamber, using fixed injection orifices, is run at roughly one half of full thrust, $P_c = 250$ lb./in.^{2} abs. and $P_i - P_c = 25$ lb./in.^{2}, so a one per cent pressure fluctuation now causes a 5 per cent mass flow fluctuation. Thus the tendency to instability increases as the thrust level decreases. This argument also explains why chugging is not often met with on turbo-jet engines, where operating pressures are generally low but fuel injection pressures are high.

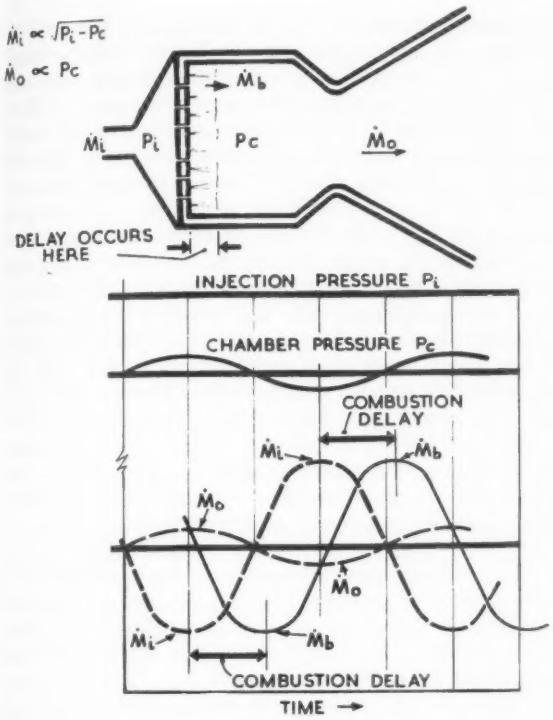

FIGURE 6. Chugging.

Although mechanically uncomfortable and thermodynamically inefficient, chugging does not usually cause immediate disintegration of the thrust chamber.

High frequency instability, or "screaming," is an acoustic resonance of the combustion chamber, usually in the tangential swashing mode analogous to "screech" or "howl" in reheat systems. The latter is caused by the interaction of the swashing gases with the flame stabilisers, which causes them to shed vortices in synchrony with the oscillation; the resulting increase in mixing increases the burning rate just when the pressure is high and so keeps the oscillation going as shown diagrammatically on Fig. 7. It is usually cured by damping out the oscillation with a perforated liner.

A similar cure is not practicable in rocket combustion chambers where wall conditions are inimical to perforated liners, so one would like to stop the oscillation at source. However, the driving mechanism cannot be the same as in afterburners, since there is no stabiliser present; and unfortunately there is as yet no agreement on the true cause of screaming. One school holds that the transverse velocities affect the sprays of the two propellants differently, blowing the vaporised oxygen through the fuel sprays and enhancing the mixing and combustion. If the amplitude of oscillation is high there will be a greater burning rate where the pressure is high, and the oscillation will be reinforced. Such an argument would explain why like-on-unlike injector arrangements, in which the impingement and mixing are very sensitive to crosswinds, are considered liable to screech. Another school holds that the oscillation is maintained by the equivalent of

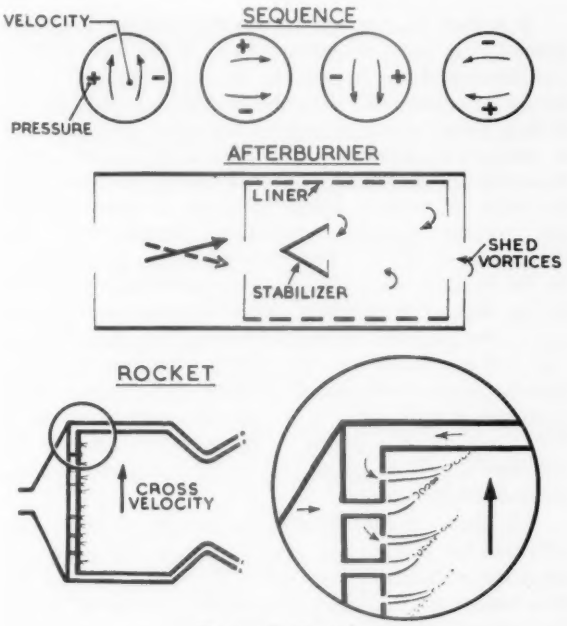

FIGURE 7. Screech.

detonation waves, surging to and fro across the chamber. In either case the oscillation can only be maintained above a certain minimum amplitude, which is in line with practical experience that screaming in otherwise stable engines can often be triggered by an over-rapid ignition—a "hard start"—or by a local explosion.

In any case the results of screech are devastating. The chamber may be destroyed in less than a second due to the combination of high oscillating stresses with the great increase in heat transfer caused by the high transverse velocities at the walls.

8. Starting

It will thus be realised that the requirement of smooth starting is paramount. This means that appreciable quantities of *both* propellants must not be allowed to accumulate in the chamber before ignition. The gas residence time in a typical chamber is only about two milliseconds, and instantaneous combustion of an accumulation of more than this quantity of the normal flow would therefore over-pressurise the chamber! Although it sounds paradoxical, the fastest starts are often the smoothest, since accumulation of propellants is prevented. Such fast starts, taking only a fraction of a second from zero to full thrust, also tend to waste less of the propellants before take-off.

With the liquid oxygen/kerosine propellant combination, liquid fuel could easily accumulate in the chamber, and react prematurely with atmospheric oxygen, if it were allowed to arrive first. If an oxygen lead start is used, on the other hand, time is allowed to chill the injector and get over any "geysering" flow fluctuations that might occur, while the oxygen injected into the chamber tends to boil fast enough to prevent accumulation. An oxygen lead start is therefore preferable.

It is then necessary to ensure that the fuel is ignited immediately upon injection. Even if the fuel/oxidant combination were hypergolic (*i.e.* self igniting) there would be appreciable delay before ignition took place: in fact, kerosine and oxygen do not react spontaneously at ambient temperatures. An external source of heat is therefore always necessary. This source must be large, for, after all, it takes about 50 watts to ignite a single gas turbine engine combustion chamber at one thousandth of the fuel flow; it must not be extinguished by the oxidant coming in all around it; it must penetrate to the edge of the injector, where the fuel usually first enters the chamber, without burning out the chamber wall before cooling fuel reaches it. To date the most popular method of ignition appears to be the use of a pyrotechnic squib, that is, a large firework, attached to the centre of the injector. However the use of an auxiliary supply of hypergolic fuel is being investigated as an ignition source.

To add to an already difficult problem we must also schedule the turbine gas supply so that (*a*) the pumps do not overspeed because power is available before the flow builds up or because cavitation is occurring due to the excessive liquid acceleration and inlet pressure drop, and (*b*) the sudden rise in pressure when the chamber ignites does not stop the flow and so start a chugging instability. If a "bootlace" system like that illustrated in Fig. 1 is used, an external starting supply system is required, and the right operating conditions for this can only be found by trial.

9. Control

Having started the engine, the next problem is how to keep it going at the desired thrust level. One possible method is to throttle both the main propellant lines. This would be quite inadmissable in a turbo-jet engine, where the work done in the compressor is such a high proportion of the turbine output, but of course in a rocket, where the working fluids are pumped as liquids, no appreciable thermodynamic loss results. The method does, however, have the disadvantage of increasing the power handled by the turbine and pumps and increasing the stresses in pumps and lines: it also introduces the complication of having to alter the main valve positions together in order to preserve the correct mixture ratio in the thrust chamber.

A preferred alternative is to throttle the turbine, either by varying the propellant supply to the gas generator or by throttling the gases upstream of the nozzles. Hot gas valves are always unsavoury, and in the case of a bi-propellant gas generator one runs the risk of upsetting the turbine inlet temperature. The easiest factor to control is the supply of propellants to the gas generator, by keeping either their injection pressures or their flows constant.

In order to reduce the turbine inlet temperature a bi-propellant gas generator always operates very far away from the stoichiometric mixture ratio, that is, a large proportion of diluent fuel or oxygen is required. Variation of the diluent flow has only a minor effect on the turbine output, the increased flow being balanced by the reduced temperature or vice versa. On the other hand variation of the flow of the propellant which is deficient produces a large change in turbine power. Thus the thrust level of the engine can be controlled stably and efficiently by keeping constant the flow or injection pressure of the deficient propellant in the gas generator.

To a first approximation, since the rocket engine carries both fuel and oxidant, and since the products of combustion are exhausted through a choked nozzle, the performance of the engine in flight is virtually independent of its environment. For example, the chamber pressure, the internal thrust and the main propellant flows, which on an air breathing engine are all directly proportional to the atmospheric pressure and profoundly affected by flight speed, are, on the rocket engine, virtually unaffected by the ambient pressure and completely independent of vehicle speed. This is of course the major advantage of the rocket engine when flight outside the atmosphere is contemplated.

On the other hand a missile carries no human pilot and is generally made independent of ground control to avoid extraneous interference. Thus any parameter which one requires to keep constant or to follow within a scheduled programme must be monitored and controlled by a servo-mechanism.

The two major engine parameters which react on the missile as a whole are the engine thrust and the propellant flow rates. However, although it is the variation, with time, of thrust and total flow rate which determine the initial trajectory of a missile in detail, it is the *overall* impulse imparted to the vehicle—that is, the quantity of propellants used multiplied by their mean specific impulse—which determines the velocity of the end of powered flight and thus the final landing point. Provided therefore that the guidance system is not disturbed by small departures from the nominal trajectory, the scheduled thrust level need only be maintained approximately. Thus the control system previously discussed, which effectively maintains constant turbine power, would probably be adequate even though it did not prevent small changes in the thrust level during flight due, for example, to the variations in pump inlet pressure, propellant density, and so on.

It is not, of course, possible to measure thrust directly in flight: to obtain the true thrust all the reactions at the points where the engine was attached to the missile would have to be summed, and allowance made for the weight and acceleration of the engine itself and for the pressure forces transferred by the propellants in the supply pipes. The engine controller cannot therefore be based on a thrust programme. However, it *is* possible to consider a guidance system in which the apparent missile acceleration is compared with a desired value throughout flight, and the resulting error signal made to control the gas generator throttle.

10. Propellant Utilisation

Far more critical than thrust control is control of the propellant mixture ratio, or rather the overall ratio in which the propellants are used. It is obviously vitally

important to ensure that both propellants are exhausted simultaneously. An error of only one per cent in mixture ratio on the 150 second flight of our hypothetical 50 ton thrust engine at a mixture ratio (oxidant: total) of 0·7 would leave $0{\cdot}01 \times 150 \times 450 \times 0{\cdot}7$, or 470 lb. of oxidant unused in the tanks, reducing the possible range by four per cent, which is a quite unacceptable figure.

As will be shown later, it is almost impossible to measure propellant flows to an accuracy closer than this value of one per cent. Even if we did, after exhaustive testing, produce a pre-calibrated engine that could be relied on under standard conditions to give a certain mixture ratio, tanking errors and variations in flight conditions would still cause unacceptable losses in range. Furthermore, any control system based on measuring instantaneous flow rates would have to allow for variations in propellant density and tanking errors as well as cumulative measurement errors. It therefore appears that all mixture ratio control systems must be based on a measurement of the instantaneous levels of propellants in the main tanks. This introduces the difficult problem of measuring accurately the mass of a liquid of variable density, sloshing around in a flimsy tank, but responsibility for this usually rests with the missile designer, so it cannot be classed as an engine problem. Once such measurement is made there is no great difficulty in comparing the relative quantities of liquid remaining with a pre-set standard and using the resulting error signal to operate valves in one or both of the main propellant lines to correct for simultaneous exhaustion.

11. Cut-off

Having now dealt with starting and control problems, the question of stopping the engine must be considered. It is interesting that this question, which has never posed much of a problem in aircraft engines, may be exceedingly important in rocket engines for ballistic missiles.

In any ground-launched missile the thrust must exceed the weight at take-off by at least 20 per cent if the vehicle is not to linger uneconomically in the atmosphere. On the other hand, to achieve ranges of the order of 1,500 miles in one stage, the propellants must comprise nearly 90 per cent of the take-off weight: thus with a simple unthrottled engine, the final missile acceleration must be of the order of $10g$, or 320 ft./sec.^{2} The velocity required at the end of powered flight is just over 15,000 ft./sec. and, allowing for the curvature of the earth, the range error for a one per cent error in final velocity is about $2\frac{1}{2}$ per cent (Fig. 8). Thus for every second that the engine continues running after the nominal cut-off point the missile travels $1{,}500 \times 2{\cdot}5 \times 320/15{,}000$, or 80 miles farther!

This is a great advantage when one has just devised a way of improving the specific impulse so that the engine runs a little longer on the same quantity of propellants. On the other hand, it means that if the missile is to arrive within one mile of the target, the guidance system must generate the stop signal at exactly

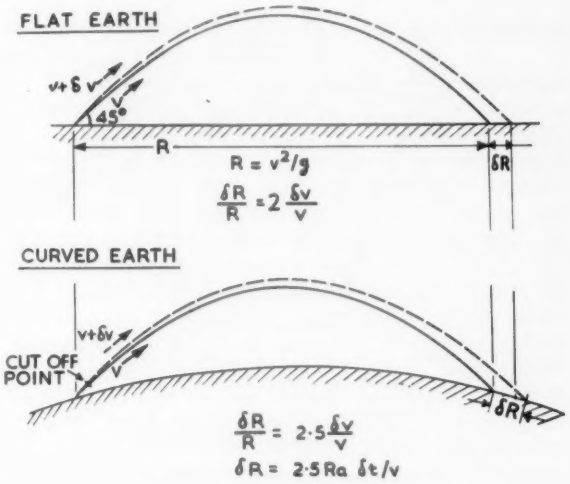

FIGURE 8. Ballistic trajectory.

the right moment: not only this, but that moment must be chosen to allow for the total impulse the engine will give after the signal has been generated and this impulse must be known to an accuracy better than the equivalent of twelve milliseconds running at full thrust. This very small permissible error has perforce to include all the engine-to-engine and test-to-test inconsistencies and variabilities, plus (unless flight results are available) the errors made in estimating the performance at altitude from results of tests on the ground and the errors in the measurements that gave those results.

One solution to this problem is obviously to stop the main engine short of the final missile velocity that is required and then to use trimming or "vernier" motors to make the final correction. This introduces a lot of complication and unreliability as well as a weight penalty and it would be preferable to control the main engine cut-off impulse to close limits. Before one can do this one must look at what happens when a rocket engine is shut down.

The normal cut-off sequence, illustrated in Fig. 9, takes place in three stages:

(*i*) The "induction" period, when the cut-off signal initiates various relays, which in turn initiate movement of the valves, usually through a pneumatic or hydraulic system: meanwhile the engine thrust continues unaltered.

(*ii*) The "decay" period while the main propellant valves actually close and the thrust decreases. The thrust measuring device, which actually records the force between the engine and its supports is unreliable during this period because of the flexibility of the supports.

(*iii*) The "hiccoughing" period, when stagnant fuel in the coolant passages evaporates, forcing the liquid farther downstream into the chamber, there to burn spasmodically with vapour from oxygen left in the injector.

In order to reduce variability in the first, "induction,"

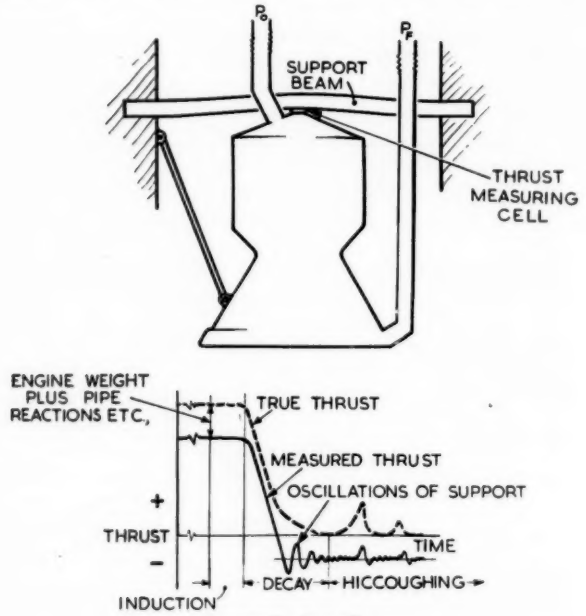

FIGURE 9. Cut-off.

period it is obviously necessary to reduce to a minimum the number of relays involved and the lengths of the pneumatic or hydraulic control lines: one possible extreme is to use the cut-off signal itself to fire a cartridge which provides gases to close the main valves almost instantaneously. The quicker the valves can be made to close, the smaller the variability of impulse provided during the second, "decay" period. However, when the time taken to close the valves is reduced below about one tenth of a second, the problem of pressure surges or "water hammer" in the main propellant lines becomes important. Burster discs or other surge suppressors are then necessary, with consequent mechanical complication and testing difficulties. The third, "hiccoughing" stage is the most variable one and also the most difficult to translate to altitude conditions, since it is quite possible that the chamber will be exhausted so quickly at very low atmospheric pressure that no spasmodic re-ignition and burning could occur.

On the other hand it must be remembered that when the back pressure is effectively zero, every pound of fuel or oxidant which evaporates, even without burning, provides some positive impulse. A possible solution is to stage the closing of the main propellant valves so that the mixture ratio after cut-off will be rich enough to extinguish any residual flame, and cool the chamber sufficiently to prevent re-ignition.

12. Instrumentation

Consideration of thrust decay rates leads on to one of the main difficulties in the assessment of rocket engine performance, namely instrumentation. Testing times are short—5 to 10 seconds is quite a common duration for a performance test—so all measurements must be recorded automatically: this involves the poor analyst in a lot of laborious trace reading afterwards. Measurement of transient conditions is, as we have just seen, very important, so we must try to keep the transducers as close to the tapping points as possible. But the environmental conditions are far from ideal—parts of the engine which are neither baking hot nor freezing cold are still subject to strenuous vibration—so transducers must either be protected by, for example, water cooling, or heating, or they must be isolated and the loss of transient response accepted.

Besides the difficulties in thrust and chamber pressure measurements already cited, measurement of transients in liquid oxygen pressures raises an extra problem because of the vapour in the relatively warm tapping lines. When the liquid pressure rises, this trapped vapour acts as a buffer and increases the response time of the transducer, since it takes appreciable time for the residual vapour to be compressed by inflowing liquid. (Fig. 10). There may also be an uncomfortable pressure surge and oscillation when the liquid finally overshoots its equilibrium position.

But above all there is the difficulty, mentioned earlier in connection with propellant utilisation, of measuring the mass flow rates, particularly that of liquid oxygen, to the high accuracy required. Errors arise from two sources—calibration, and density correction.

The normal way of calibrating a flowmeter is to pass a known mass or volume of liquid through it. Complications arise when the liquid involved is "cryogenic" that is its vapour pressure at room temperature is well above one atmosphere, as is the case with liquid oxygen. First, the correct liquid must be used, since the flowmeter will shrink in it and the flow distribution may be affected by the heat transfer at the walls. Then, if one attempts to weigh the quantity passing through, allowance must be made for evaporation, or for condensation, in the weighing area, and for a possibly variable density change of the fluid between tank and flowmeter. If one attempts to pass the volume

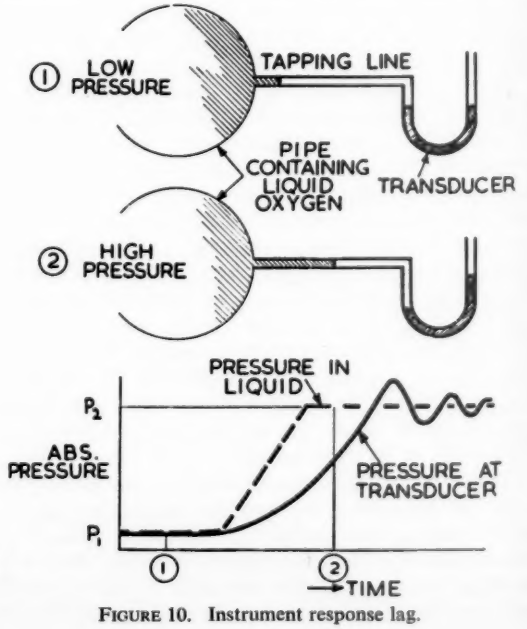

FIGURE 10. Instrument response lag.

of fluid from a calibrated tank through the meter, an additional allowance must be made for the shrinkage of the tank since its calibration with water.

Since none of the so-called "direct" mass flow measuring devices has yet been developed to a point where it can handle the huge flows involved with adequate accuracy, and with a pressure loss low enough not to cause cavitation difficulties in the pumps, a density correction must be added to the calibration. Unfortunately the density of liquid oxygen varies rapidly with temperature, by $\frac{1}{2}$ per cent per C deg., and it is not easy to measure accurately temperatures of the order of $-183°C$ in a flowing stream.

One must admit, therefore, that even with the best instruments at present available it is very difficult to guarantee an overall accuracy of oxygen flow measurement better than one per cent.

13. Performance Analysis and Prediction

With all these doubts and difficulties, few of the measurements taken on a test bed run can be expected to be within one per cent of the true value, although, if the engine is believed to be more consistent than the instruments, the error of the mean can be reduced by repeated check tests. The performance of the various engine components, gas generator, turbine, thrust chamber, and so on, can be analysed in the usual way and their characteristics obtained. It is when we try and reverse this process, and use these characteristics to predict the performance of a complete engine at conditions under which it has not been tested that difficulties arise.

These difficulties are *not* a feature of the rocket engine itself, which is basically a simple device, but arise because of the way in which it is used. For a start, the performance of a missile depends so critically on that of its propulsion system that small variations, particularly in mixture ratio become very important, and must be calculated and allowed for in advance. Secondly, the entire operation of the engine after launch is automatic: thus every component seems to react on every other component, and a line diagram of these interactions forms a glorious Gordian knot of intertwined servo loops. In fact, on one large engine it took six man-weeks to solve correctly the 67 linear simultaneous equations involved in calculating one flight performance point. With increased experience such a job can be done manually in three man days, but even an electronic digital computer needs a minute or two.

A modern turbo-jet such as a two spool by-pass engine with mixing in the jet pipe, is not uncomplicated: why should the performance of a rocket engine seem so much more difficult to predict? The answer is that, because the complete unit with both liquid and gas flows is involved, the possibilities of dimensionless analysis are very limited. Whereas the performance of most individual components can be expressed in dimensionless form, these performances cannot easily be lumped together, as they can in turbo-jet analysis, because different groups are involved in different components: in a few really difficult cases, such as the dissociation calculations in the thrust chamber itself, absolute values are themselves important, so dimensionless analysis is quite impossible.

Furthermore, the inapplicability of dimensionless analysis increases the number of independent variables. On a typical turbo-prop engine, for instance, there might be five different parameters affecting the performance of a given engine: for example, flight speed, nacelle temperature (T_1) and pressure, throttle setting and propeller pitch. The pilot automatically simplifies the last two variables to engine speed (N), and jet pipe temperature (T_4): dimensional analysis then reduces the independent variables to only three, flight Mach number, N/T_1 and T_4/T_1, the first of which has little effect anyway. It is therefore possible in quite a short time to calculate the performance of such an engine in any conceivable flight situation.

On the other hand, while the rocket engine for a missile may also be affected by the variations of five basic parameters (two pump inlet pressures, two propellant densities and, say, the throttle setting) these are all dimensionally independent, so that exploration of all possible permutations and combinations is a long job. Not only that, but atmospheric pressure may have a small effect, if any of the controls are based on gauge pressure, while the mixture ratio controller setting may add a seventh variable. The only saving grace is that the input parameters usually only vary over quite small ranges. It is therefore permissible to hope that their effects are linear and independent: sets of "influence coefficients" can then be calculated, each set showing the effect of a one per cent change in one of the input variables, for example fuel density or oxygen pump inlet pressure, on the thrust, mixture ratio and other engine operating conditions.

14. Reliability

This final subject does not always come within the scope of the performance engineer, and the term must first be defined exactly.

The "operational reliability" of an engine is defined as the probability that, all normal pre-flight checks having been completed, the engine will start when required, run in a stable manner, and cut-off when required, all with a performance within the prescribed tolerances. Reliability therefore includes consistency of performance as well as mechanical soundness. It must not be confused with "serviceability," which is the chance that no defect will be discovered on serviceing. Although "time between overhauls" is often quoted in aircraft circles as a criterion of reliability it is really this same probability of failure that is of prime importance to the user. This is particularly true in the civil business, where unpremeditated delays inevitably lead to poor passenger relations and the time between overhauls is really dictated by an implied limit on this probability of failure.

In comparing the standard of reliability of the propulsion system of a ballistic missile with that needed by air-breathing engines for aircraft, one sees immediately a major difference in the requirements. In the aircraft case human lives are directly involved in a flight

failure: in a missile they are not; there have been a number of failures in the American ballistic missile test programme, for example, but no life has been lost. The enormously high reliability required of an aircraft engine is therefore not necessary on a missile engine, and the choice of an acceptable figure for the latter is mostly a question of economics or politics. Of course rocket engines are always designed for 100 per cent reliability: no designer ever consciously builds unreliability into a system. But the cost of developing a large engine of high reliability, and of proving that such reliability has been obtained, increases astronomically as the reliability approaches unity: and if 100 missiles are to be built it is not economical to continue development after the cost of improving the reliability by one more percentage point has become greater than that of providing and operating one extra missile. This may well occur when the overall operational reliability is only 70 per cent, so that one would accept an engine reliability in the nineties, errors in guidance, structure failures, and so on, taking up the rest of the permissible unreliability.

This big discrepancy between the unreliability values that one would accept on aircraft and missile engines leads to different methods of assessing reliability.

It takes a year or two of intensive flying to demonstrate that an engine fulfils the typical requirements of one engine failure per million take-offs or per 100,000 flights. It is therefore usual to demonstrate potential reliability by accelerated endurance tests, the provisional 25 hour special category test, and the final 150 hour type approval test, which both contain an abnormally high proportion of high speed running. These are supposed to produce conditions so much more onerous than normal flying that they prove the factors of safety necessary to give the desired minimum failure rate between overhauls.

On the other hand the engine for a ballistic missile is designed for a short operational life of less than three minutes, probably all spent at maximum thrust. In this time very few components wear out, and the incidence of failures is therefore fairly random. Thus there is no point in attempting the equivalent of the 150 hour type test with its overload and endurance categories. What is needed is to perform a large number of standard tests, and discover the proportion of successes.

This at once raises the question of whether the same engine must be used for all tests. If, as was suggested, failures are random, then obviously more than one engine may be used. In fact, on any normal statistical distribution, there is at least a 50 per cent chance that an engine will fail before the average reliability has been demonstrated.

However, a large number of tests may be required to demonstrate a reliability of even 90 per cent with a degree of confidence acceptable to the statistician. Rather than attempt a fixed sample test, therefore, it is usual to analyse the results as they are obtained. In this "sequential" analysis the testing continues until either there have been so many failures that the chance

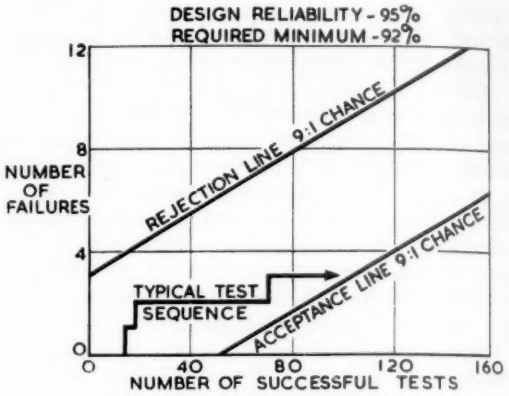

FIGURE 11. Sequential analysis.

that the engine is really as good as the maker claims is very small compared with the chance that it is worse than will be accepted by the user: or conversely there have been so many successes that the chance that the engine is as good as the makers claim is many times greater than the chance that it is worse than the users require (Fig. 11). Each side then takes a risk; the producer that his good engine type will be rejected, the user that a poor engine will be accepted. It is usual, if the engine is under continuous development, to plot the results backwards so that recent tests are given more weight. A final refinement in this statistician's paradise is to choose the producer's and user's risks so that the maximum cost of making a wrong decision is as small as possible.

One final small point on the subject of failures is of interest. While the engine is still on test, or on the launching platform, it should be made to shut down automatically in the event of failure, for example an interruption of the electrical supply. On the other hand once the missile has left the launcher it must keep going at all costs. Thus the "fail safe" direction undergoes a complete reversal at take-off, and a good design must take account of this.

15. Conclusions

This paper is intended to show that performance problems do exist in large rocket engines, that they are different from those on air breathing engines, and that they have their own fascination. At the present time the major difficulties are probably those introduced by thrust chamber heat transfer, combustion instability, propellant utilisation, cut-off repeatability and instrumentation. If the presentation of the paper, or any discussion it provokes, leads to any new ideas on these subjects, it will have been well worthwhile.

ACKNOWLEDGMENTS

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Stress Distribution Around a Central Crack in a Plate Loaded in Tension; Effect of Finite Width of Plate

by

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SUMMARY: The purpose of the work was to investigate the effect of the finite width of plate on the elastic-stress distribution due to a central crack in a flat plate loaded in tension.
The range of investigation: (*i*) Two-dimensional photoelastic tests were carried out on flat-plate specimens. The photoelastic specimens were geometrically similar to the 10 in. wide fatigue specimens used by Frost and Dugdale[1], with the central crack simulated by a slot bounded by holes of small radii. (*ii*) A theoretical solution of the problem was derived and compared with the present and other photoelastic results.
It is shown that the effect of the crack-length/plate-width ratio on the elastic-stress concentration at the head of the crack can be expressed by the following formulae:

$$\frac{K_m}{K_\infty} = \left(\frac{1-l/b}{1+l/b}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (1)$$

$$\frac{K}{K_\infty} = (1-l^2/b^2)^{-\frac{1}{2}} \quad \text{for } 0 \leqslant l/b \leqslant 1 \; . \quad . \quad . \quad (2)$$

1. Introduction

Although many exact theoretical solutions exist for the two-dimensional stress distributions in plates of infinite width containing holes of various shapes, the mathematics become lengthy and complex when plates of finite width are considered; and except for the particular case of a circular hole, little information is available.

The object of the photoelastic investigations was to find out the effect of the crack-length/plate-width ratio on the stress distribution in a fatigue specimen containing a central crack. The results of these photoelastic tests and others were then compared with a theoretical solution, in an attempt to derive a relationship between K_m, K and l/b that would be of general use.

NOTATION

K_m	ratio of maximum stress at head of crack to nominal stress across net section
K	ratio of maximum stress at head of crack to nominal stress across gross section
K_∞	ratio of maximum stress at head of crack to nominal stress across the plate, in a plate of infinite width
$2l$	crack length
$2b$	plate width
$2u$	amount of opening of crack under load
E	Young's modulus
T_0	nominal stress across the gross section of plate

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2. Photoelastic Specimen

It is not possible with the normal photoelastic techniques to determine the stress distribution at the head of an actual crack. In order that measurements can be made the crack must be simulated by a slot with small end radii.

The photoelastic specimen was made of Araldite casting resin B and machined geometrically similar to the 10 in. wide fatigue specimens used by Frost and Dugdale[1]. The central crack was simulated by a narrow slot bounded by holes of radii 0·028 in. Details of the specimen are given in Fig. 1.

Load was applied through clamped end plates, in a similar fashion to the actual fatigue specimen.

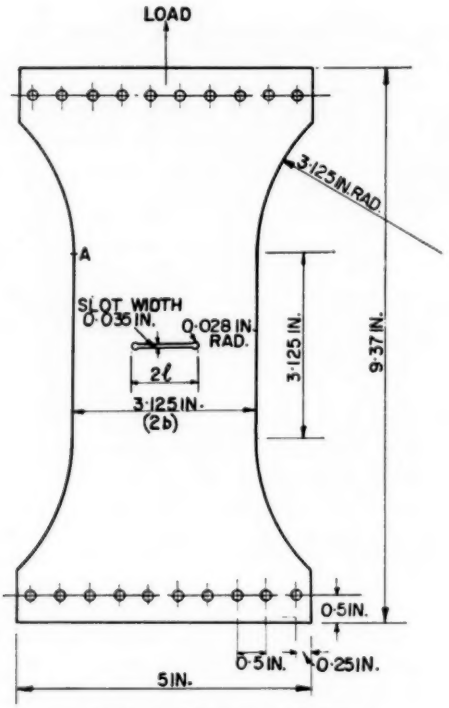
3. Method of Test

The loading and optical analysis was carried out using normal two-dimensional photoelastic techniques. The interference fringes near the ends of the slot were measured using a travelling microscope focused on an enlarged image of the fringe pattern. Readings were taken as near as possible to the end of the slot, and boundary values obtained by graphical extrapolation.

The slot was lengthened in increments of 0·4 in., its ends bounded by holes of radii 0·028 in. at each stage. A photograph of a typical isochromatic-fringe pattern is shown in Fig. 2.

4. Results

For each l/b ratio tested, the maximum stress at the end of the slot was determined, and expressed as a stress concentration factor, K_m or K. These results are given in Table I, and plotted in Figs. 3 and 4.



Specimen thickness: 0·0625 in.
Material: Araldite B.

FIGURE 1. Photoelastic specimen.

It was noticed that the regions of uniform tension in the parallel part of the specimen, between the slot and loading plates, ceased to exist for $l/b > 0{\cdot}2$. This implies that the stress distribution around the slot would not be independent of loading conditions. An idea of the magnitude of the effect of loading conditions can be obtained from results of a similar series of photoelastic tests (Dixon[2]); these results, given in Table II, and

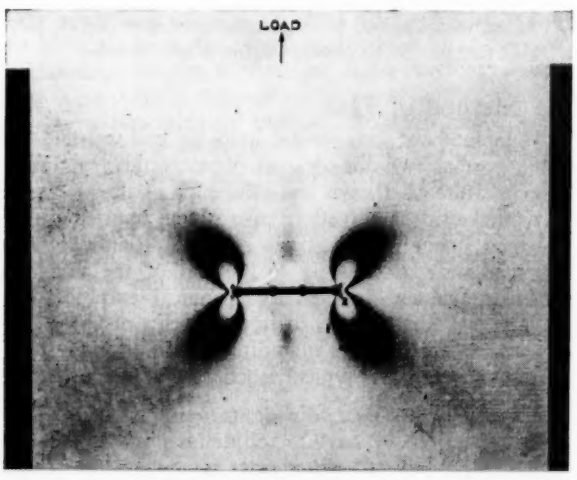


FIGURE 2. Isochromatic fringe pattern for slot-length/plate-width = 0·207. Nominal stress across net section = 724 lb./in.² Fringe value of model = 892 lb./in.²/fringe principal stress difference. (Numbers 1 and 2 denote fringe order.)

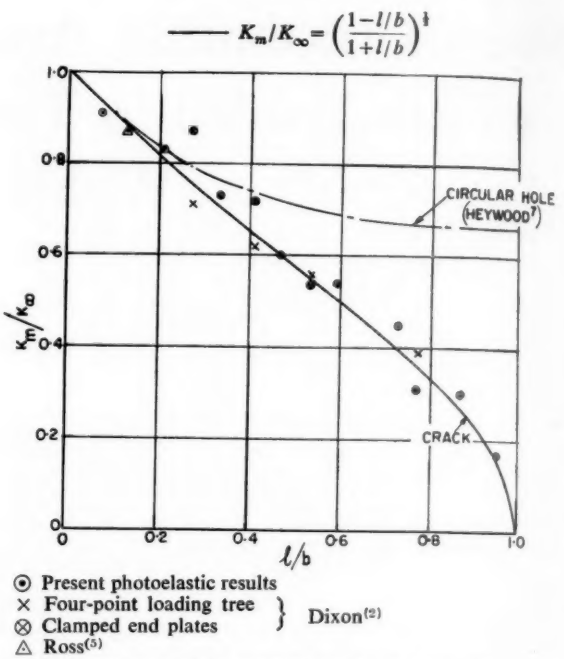


FIGURE 3. Effect of finite width of plate on K_m

plotted in Figs. 3 and 4, show the difference in K_m and K when load is applied through clamped end plates or through a four-point loading tree.

Figure 5 shows the variation of the separate longitudinal (Y) and transverse (X) stresses across the parallel part (LM) of the specimen near the fillet, for $l/b = 0{\cdot}47$. The X and Y stresses were obtained from a numerical integration of the elastic equations of equilibrium using data obtained from photoelastic measurements.

The stress-concentration factor (based on nominal stress across the parallel part) in the unslotted specimen at the run-out of the fillet (point A, Fig. 1) was 1·22.

5. Theoretical Solution

Coker and Filon[3] made an approximate theoretical treatment of the general problem of a central elliptical hole in a plate of finite width loaded in tension. The following relationship was obtained:

$$\frac{K_m}{K_\infty} = \left(1-\frac{l}{b}\right)\left[1-\frac{1}{2}\left(\frac{l}{b}\right)^2-\frac{1}{8}\left(\frac{l}{b}\right)^4\left(1+\frac{d}{l}\right)\left(1-\frac{d}{l}+2\frac{d^2}{l^2}\right)-\frac{1}{16}\left(\frac{l}{b}\right)^6\left(1+\frac{d}{l}\right)\left(1-\frac{d^2}{l^2}\right)\left(1-\frac{d}{l}+4\frac{d^2}{l^2}\right)+O\left(\frac{l^8}{b^8}\right)\right]^{-1}$$

for "small" l/b . . . (3)

where $K_\infty = 1+2l/d$ (Inglis[4]) . (4)

Using a similar theoretical approach to Coker and Filon, it is shown in the Appendix, that for a central crack ($d=0$),

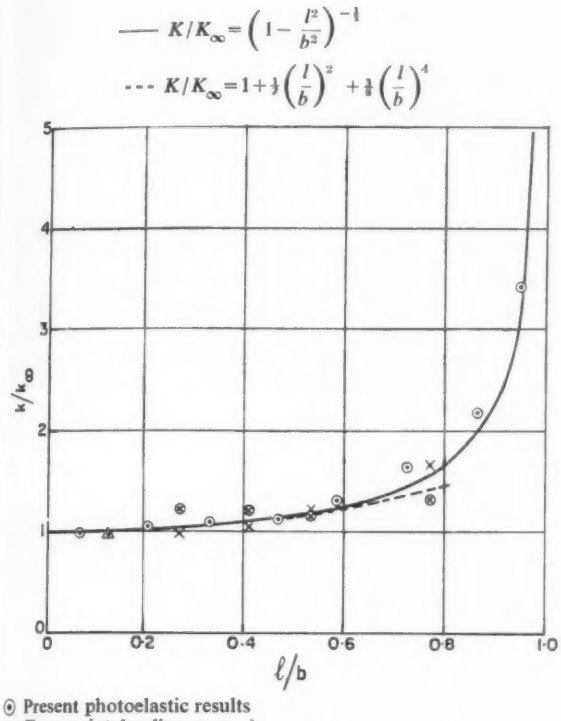


FIGURE 4. Effect of finite width of plate on K.

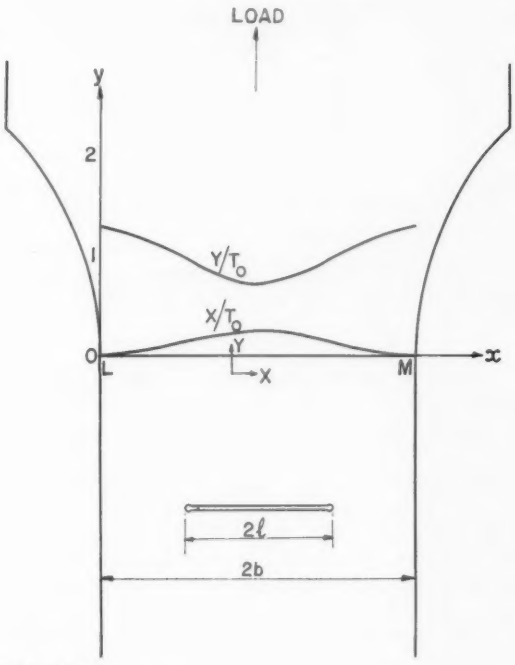


FIGURE 5. Variation of stress across LM.

TABLE I

STRESS-CONCENTRATION FACTORS. RESULTS FROM PRESENT SERIES OF PHOTOELASTIC TESTS.

$\frac{l}{b}$	*Photoelastic*		*Theoretical*	$\frac{K_m}{K_\infty}$	$\frac{K}{K_\infty}$
	K_m	K	K_∞		
0·074	4·63	5·01	5·08	0·91	0·99
0·207	6·48	8·17	7·80	0·83	1·05
0·337	7·07	10·68	9·70	0·73	1·10
0·466	6·81	12·77	11·30	0·60	1·13
0·592	6·74	16·53	12·52	0·54	1·32
0·727	6·21	22·72	13·76	0·45	1·65
0·862	4·45	32·31	14·76	0·30	2·19
0·950	2·59	52·20	15·32	0·17	3·41

TABLE II

STRESS-CONCENTRATION FACTORS. RESULTS FROM PREVIOUS PHOTOELASTIC WORK

$\frac{l}{b}$	*Photoelastic*		*Theoretical*	$\frac{K_m}{K_\infty}$	$\frac{K}{K_\infty}$	
	K_m	K	K_∞			
0·275	7·1	9·7	9·94	0·71	0·98	*p*
0·275	8·7	12·1	9·94	0·87	1·22	*q*
0·410	7·4	12·5	11·92	0·62	1·05	*p*
0·410	8·6	14·4	11·92	0·72	1·21	*q*
0·535	7·6	16·4	13·48	0·56	1·22	*p*
0·535	7·3	15·8	13·48	0·54	1·17	*q*
0·770	6·2	26·8	15·98	0·39	1·68	*p*
0·770	4·9	21·0	15·98	0·31	1·32	*q*
0·127	7·98	9·14	9·22	0·87	0·99	Ross(5)

Dixon(2)

Note: *p* denotes load applied through a four-point loading "tree".
q denotes load applied through clamped end plates.

$$\frac{K_m}{K_\infty} = \left(\frac{1-l/b}{1+l/b}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (5)$$

$$\frac{K}{K_\infty} = (1-l^2/b^2)^{-\frac{1}{2}} \quad . \quad . \quad (6)$$

6. Comparison between Theory and Experiment

The values of K_∞ for the particular type of slot used in the photoelastic tests are obtained from:

$$K_\infty = 1+2\sqrt{(l/\rho)} \text{ (Inglis[4])} \quad . \quad . \quad (7)$$

where ρ = radius of curvature at end of slot.

Values of K_m/K_∞ and K/K_∞ for the present series of photoelastic tests are given in Table I, and for the previous work of Dixon[2] and Ross[5] in Table II.

The theoretical curves and experimental points are plotted in Figs. 3 and 4. It was not obvious from the assumptions made (*see* Appendix), about the distribution of stress (f) across the net section in a plate of finite width, for what range of l/b the theory would apply. Figs. 3 and 4 show the agreement between the theoretical and experimental results to be good for the whole range of l/b tested.

It can be shown from (3) that the difference in K_m/K_∞ for $d/l=0$ (crack) compared with the small but finite values of $d/l=\sqrt{(\rho/l)}$ for the slot in the photoelastic tests is negligible.

It is interesting to note that the expression K_m/K_∞ for a circular hole, obtained by putting $d=l$ in (3), does not agree with the theory of Howland[6], and empirical law of Heywood[7], for $l/b>0{\cdot}1$. This shows that (3) cannot be used for large l/b values, when d/l is also large.

7. Conclusions

The effect of the crack-length/plate-width ratio on the elastic stress concentration at the head of a central crack in a plate loaded in tension can be expressed by:

$$\frac{K_m}{K_\infty} = \left(\frac{1-l/b}{1+l/b}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (8)$$

$$\frac{K}{K_\infty} = (1-l^2/b^2)^{-\frac{1}{2}} \quad . \quad . \quad (9)$$

for $0 \leqslant l/b \leqslant 1{\cdot}0$.

Frost and Dugdale[1], on 10 in. wide fatigue specimens, measured the amount of opening of a central slit as load was applied. The results suggested that:

$$\frac{Eu}{2T_0 l} = 1+A\left(\frac{l}{b}\right)^2 \quad 0 \leqslant l/b \leqslant 0{\cdot}4$$

and $0<A<1$. . . . . (10)

Assuming that the amount of opening was proportionate to the stresses in the elastic material surrounding the slit, then (9) and (10) are in good agreement; since from (9),

$$\frac{K}{K_\infty} = \left(1-\frac{l^2}{b^2}\right)^{-\frac{1}{2}} = 1+\frac{1}{2}\left(\frac{l}{b}\right)^2 + \frac{3}{8}\left(\frac{l}{b}\right)^4 + O\left(\frac{l}{b}\right)^6$$

(*see* Fig. 4). . . . . (11)

Heywood's[7] empirical expression

$$\frac{K_m}{K_\infty} = 1-\frac{l}{b}+\left(\frac{l}{b}\right)^2 - \frac{1}{3}\left(\frac{l}{b}\right)^3$$

for a circular hole of radius l, is plotted in Fig. 3. Heywood's curve for a circular hole and the curve for a crack (Fig. 3) can be regarded as limiting cases of the family of curves ($K_m/K_\infty, l/b$), representing the general solution of a central elliptical hole in a plate of finite width, under a tensile load (the major axis of the ellipse perpendicular to the direction of the applied load, and major axis $\geqslant$ minor axis).

ACKNOWLEDGMENTS

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APPENDIX

THEORETICAL ANALYSIS

NOTATION (*see* Fig. 6)

$2b$	width of plate
$2l$	length of major axis of ellipse
$2d$	length of minor axis of ellipse
T_0	nominal stress across the gross section of plate
T_m	nominal stress across the net section of plate
ξ, η	curvilinear co-ordinates; $x=c\cosh\xi\cos\eta$, $y=c\sinh\xi\sin\eta$
f	stress acting across the net section.

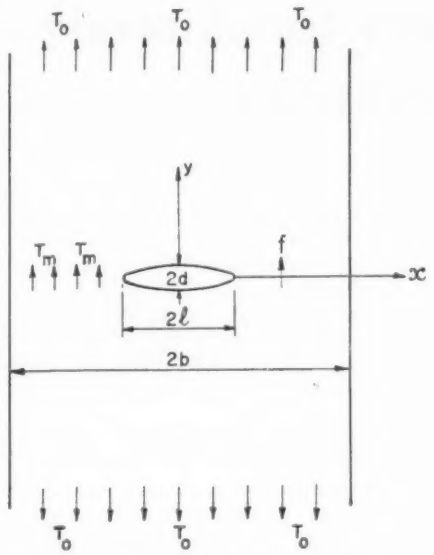

FIGURE 6. Notation for Appendix.

CENTRAL ELLIPSE IN A PLATE OF FINITE WIDTH

For a plate of infinite width ($b=\infty$), the exact theory[3] gives:

$$\frac{f}{T}=(1-e^{-2\xi})^{-4}\left\{1+e^{-2\xi}(\cosh 2\alpha-3)+\frac{3}{2}e^{-4\xi}(e^{2\alpha}-1)^2+\right.$$

$$\left.+e^{-6\xi}\left(1+\frac{7}{2}e^{2\alpha}-\frac{1}{2}e^{-2\alpha}-2e^{4\alpha}\right)+\frac{1}{2}e^{-8\xi}(e^{4\alpha}-2e^{2\alpha}-1)\right\} \quad (1)$$

where $T=T_m=T_0$ for $b=\infty$.

The elliptical hole is given by $\xi=\alpha$, hence $\tanh\alpha=d/l$.

For a plate of finite width, assume that f is given by (1), where T is a function of b, l and T_m, and not initially known.

To determine T, equilibrium across the net section gives:

$$T_m(b-l)=\int_l^b f\,dx \quad . \quad . \quad (2)$$

where f is given by (1).

Integrating (2), it can be shown[3] that

$$T_m(1-l/b)=$$

$$T\left\{1-\frac{1}{2}\left(\frac{l}{b}\right)^2-\frac{1}{8}\left(\frac{l}{b}\right)^4\left(1+\frac{d}{l}\right)\left(1+2\frac{d^2}{l^2}-\frac{d}{l}\right)-\right.$$

$$\left.-\frac{1}{16}\left(\frac{l}{b}\right)^6\left(1+\frac{d}{l}\right)\left(1-\frac{d^2}{l^2}\right)\left(1-\frac{d}{l}+4\frac{d^2}{l^2}\right)+O\left(\frac{l}{b}\right)^8\right\} \quad (3)$$

Since $bT_0=(b-l)T_m$

$$T_0=(1-l/b)\,T_m=\text{R.H.S. (3)} \quad . \quad . \quad . \quad (4)$$

f, for a plate of finite width is then given by:

$$\frac{f}{T_m}=\left(\frac{f}{T}\right)_{b=\infty}\times\frac{T}{T_m} \quad . \quad . \quad . \quad (5)$$

or

$$\frac{f}{T_0}=\left(\frac{f}{T}\right)_{b=\infty}\times\frac{T}{T_0} \quad . \quad . \quad . \quad (6)$$

where $\left(\frac{f}{T}\right)_{b=\infty}$ is given by (1), and $\frac{T}{T_m}$, $\frac{T}{T_0}$ by (3) and (4).

CENTRAL CRACK IN A PLATE OF FINITE WIDTH

For the particular case of a crack ($d=0$), equation (2) can be integrated without the use of infinite series as in (3).

For $d=0$, $\tanh\alpha=d/l=0$

therefore $\alpha=0$, and $l=c\cosh\alpha=c$

Also, $x=l\cosh\xi$

therefore $\frac{dx}{d\xi}=l\sinh\xi$.

Equation (1) simplifies to

$$\frac{f}{T}=\frac{1+e^{-2\xi}}{1-e^{-2\xi}}=\coth\xi \quad . \quad . \quad . \quad . \quad (7)$$

Equation (2)

$$T_m(b-l)=\int_l^b f\,dx$$

becomes

$$T_m(b-l)=Tl\int_{x=l}^{x=b}\coth\xi\sinh\xi\,d\xi=Tl\int_{\xi=0}^{\xi=\cosh^{-1}b/l}\cosh\xi\,d\xi$$

$$=Tl\left[\sinh\xi\right]_{\sinh\xi=0}^{\sinh\xi=\frac{b}{l}\left(1-\frac{l^2}{b^2}\right)^{\frac{1}{2}}}$$

$$=Tb\left(1-\frac{l^2}{b^2}\right)^{\frac{1}{2}}$$

therefore $\frac{T}{T_m}=\frac{(1-l/b)}{(1-l^2/b^2)^{\frac{1}{2}}}=\left(\frac{1-l/b}{1+l/b}\right)^{\frac{1}{2}}$ . . (8)

From (4), (5) and (6),

$$K_m=\frac{f_{(max.)}}{T_m}=K_\infty\times\frac{T}{T_m}$$

therefore $\frac{K_m}{K_\infty}=\left(\frac{1-l/b}{1+l/b}\right)^{\frac{1}{2}}$ . . . . (9)

$$\frac{K}{K_\infty}=(1-l/b)^{-1}\frac{K_m}{K_\infty}=(1-l^2/b^2)^{-\frac{1}{2}}. \quad (10)$$

For the experimental results, K and K_m were determined from the photoelastic tests; K_∞ was determined from the well-known formula

$$K_\infty=\frac{f_{(max.)}}{T}=1+2l/d=1+2\sqrt{(l/\rho)}$$

which can be obtained by putting $\xi=\alpha$ in equation (1).

Operational Requirements for Aircraft in Australian Territories

by

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AT ITS FIFTH Meeting, the Commonwealth Advisory Aeronautical Research Council discussed the need for a better understanding of the operational requirements for aircraft in different parts of the Commonwealth. It therefore asked for papers from the respective countries, bearing in mind particularly the possibilities of V.T.O.L. and S.T.O.L. aircraft.

A survey has been made in Australia. The general impression gained is that within the Australian continent there are no outstanding future operational needs, if the term outstanding is interpreted in the sense of V.T.O.L. or S.T.O.L. or other extraordinary condition of operation. This is not surprising since Australia has, on the whole, excellent conditions for flying; there are no high mountains, very little icing or fog, and the country tends generally to be flat and low. In external operations conditions are not so favourable and certain definite requirements emerge. These, together with some general observations, have been recorded as of interest to designers. It is clear that simpler forms of V.T.O.L. aircraft than rotary winged types are needed, and this may well indicate a need for more research.

Air Transport on the Australian Mainland

The greater part of Australian air traffic occurs between the capital cities and seems particularly suited to the type of commercial aircraft highly developed and readily available overseas. There does not appear to be any peculiarly Australian requirement for this traffic; in fact the mainland is fortunate because virtually all the aerodromes are at low level with no really difficult approaches.

There is one reservation. While the general characteristics of the civil aircraft being developed overseas fit the Australian requirements for aircraft on main routes, their size is becoming too great. This is shown by an analysis of the productivity of various available types, productivity being defined as the number of passenger miles the aircraft can achieve annually at 75 per cent load factor and an annual utilisation of 3,000 hours. The figures vary from 103 million passenger miles for the Boeing 720 down to 48 million for the Electra (the type chosen for the longer Australian runs). The Viscount, used on shorter runs has a productivity of 26 million passenger miles. These figures for a single aircraft must be compared with a total traffic of 400 million passenger miles for each of the two major airlines, of which only about one-quarter is flown by the larger aircraft. Thus, one Boeing 720 would handle all the traffic but result in an impractical time-table.

The question of size looms large in Australia, which differs from other countries in that the airlines run some extremely low traffic density "homestead" routes with frequencies as low as one flight per fortnight. The following factors are against the development of special aircraft for these routes: very few will be required; they would necessarily be small aircraft and therefore uneconomic to operate; airlines prefer in the interests of fleet standardisation to use an existing type (from say feeder line service) even though it costs even more in direct operating costs. Furthermore the use of a larger than necessary aircraft appears to attract traffic. As an example of the latter effect, the case has occurred on this type of run when the Dakota replaced the Drover in order to standardise the airline fleet. The increase in freight which occurred more than covered the increased direct operating cost of the larger aircraft. Because of the rather poor runway surfaces on smaller airfields, tyre pressures of feeder line aircraft should be low, *e.g.* 60 p.s.i. mainwheels, 40 p.s.i. nosewheel.

In certain restricted parts of Australia, such as the Gulf country, there is a need for an even smaller type of aircraft than the Dakota or the Friendship to operate on routes of about 500 miles in 50 to 60 mile stages. The aircraft should be able to operate from relatively short runways, *i.e.* not longer than 1,800 feet. A payload of 2,000 lb. would be required and this must be readily interchangeable between passengers and freight; for this purpose the fuselage cross section should not be too small. A cruising speed of 150 m.p.h. is necessary. The aircraft should be capable of operation by a single pilot and with a minimum of ground services. It should have twin engines for safety.

These tertiary routes are not likely to be economic, but would be acceptable if costs of 8d. to 9d. per passenger mile at 50 per cent load factor could be achieved. Air freighting would not be economic at the road transport cost of 16d. per ton mile, but it would pay the airline to fill surplus capacity rather than run with partial loads.

Helicopters and V.T.O.L. Aircraft

The penalties of performance implicit with V.T.O.L. or S.T.O.L. type aircraft are sufficient to limit their use to operations where normal aircraft cannot operate,

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whereas the Australian mainland seems to be particularly suited to normal civil aircraft operations.

Nevertheless, as in other countries, there are certain operations which can only be carried out by helicopters; moreover, other operations particularly of the survey type in difficult terrain are enormously speeded up by their use. However, the numbers in use throughout Australia are not great. Australian helicopter requirements would not differ from those overseas. Thus, certain types of crop dusting, for example potatoes, are being done economically as the downwash is particularly useful, but this is not peculiar to Australia.

The main drawback of V.T.O.L. aircraft is cost. Much greater use would be made of helicopters if the cost of a small aircraft could be reduced to £A25 per hour instead of the present minimum cost of £A45. This points the need to some simpler principle than the rotary wing.

Freight Operations

The existing rates for air freight tend to make the use of special freight aircraft uneconomic. The ideal freight traffic density is such as to allow a freight pool to be on hand to "top up" passenger aircraft during off peak periods. Some freighters are necessary to attract this traffic, but one of the two major airlines has difficulty in utilising even a single freight aircraft, while the other probably loses money with every freighter flight.

Aircraft in the Antarctic

Australia has an interest in a large part of Antarctica. In such a huge continent, air transport is the obvious choice, but aircraft can be landed in comparatively few areas. Most of the ice is old (*i.e.* non-glacial) and very rough; moreover, no smoothing by a snow cover occurs because the snow gets blown away by the strong winds. The flying is done from Mawson mainly during the summer months, when it is unusual for the ground temperature to fall below $-20°F$. Further inland and during the winter the temperatures are much lower.

The real interest in this area lies in the mountain ranges which rise out of the ice to heights of up to 12,000 feet. Here the mineral wealth of Antarctica will be found if it exists; elsewhere there is nothing but many thousands of feet of ice. In the Australian sector, the mountains lie to the south of Mawson within a radius of 400 miles. There are extremely few places in or near the mountains where even a light aircraft can be landed and the detailed minerographic exploration must be carried out on foot or with dog sleds.

The requirement therefore arises for a V.T.O.L. aircraft of a definite specification:

Payload	2,000 lb. (4 passengers + 1,000 lb. of equipment).
Range	Not less than 400 miles. Ideally, it should have a radius of operation of 400 miles without refuelling.
Performance	Operating heights from 6,000 to 14,000 feet. Very turbulent conditions are encountered so that control and rate of climb must be good at these altitudes.
Reliability	The equivalent of twin engined safety is required.

At the present time no such aircraft exists and the number required in this particular area will be very small indeed. Thus, unless some new principle of V.T.O.L. operation substantially less complex than the rotary wing is evolved, the development of a special type to meet Antarctic requirements seems remote.

Operations in New Guinea

The general background of New Guinea operations is one of a rapidly developing area with a corresponding development of facilities, so that the pressing aeronautical problems which existed a few years ago no longer exist because of the rapid expansion and importance of aerodromes in the coastal region.

A second aspect of operations in this area is the major importance of the economic factors which tend to exert a decisive influence on the choice of aircraft and which goes beyond purely technical considerations. Thus even if the operators specified an ideal type of aircraft for their conditions and this specification could be met, the solution might still be unacceptable on economic grounds such as the financial arrangements for purchase and the type of service backing provided by the manufacturer.

It is clear that the foregoing considerations render it extremely difficult to formulate short-term requirements, but it might well be that longer term problems, looking at the far future of New Guinea operations, could give rise to research projects. However, there does not appear to be a sufficiently settled Government policy in regard to the future of air operations in New Guinea for such long-term thinking to be done; thus, as far as is known, there exists no investigation of long-term aircraft requirements.

It is felt that in spite of the foregoing statement there is a pressing need for operational research support in such fields as Human Engineering, Production Planning and Aircraft Operations. In explanation, Production Planning would be regarded as the scientific planning of stores procurement and the deployment of stores through various routes in order to support aircraft operations. This type of scientific planning would have regard to the probability of component failure, the cost of spares provisioning and the contingent cost of delays if spares were unavailable in certain locations. Intensive records exist but they require scientific analysis.

Finally, it should be stated that the unusual aircraft operations are mainly associated with commercial enterprises such as oil search. In general, helicopters or very light aircraft are used. However, roads are being rapidly extended because it would be uneconomic to use air transport as was done in the early days of the goldfields. There is no special feature in these operations apart from the fact that single engine safety standards are accepted over extremely difficult terrain.

Agricultural Aircraft

Australia has benefited considerably from studies of the U.S.A. and New Zealand policy and practice in the use of aircraft for agricultural purposes. Operating conditions are roughly the same as in the U.S.A. whereas in New Zealand, the conditions and requirements tend to be very different.

In agricultural operations, cost is a prime consideration and this involves low operating, maintenance and repair costs. In the past, this has led to the use of disposals aircraft of unsuitable type and to undesirable practices, and the present policy is to place the industry on a more solid basis and to get rid of cut price operators working on unsafe margins. Again, contracts are tending to become larger so that the use of large heavily loaded aircraft for the main areas with smaller machines for mopping up edges and corners of fields is coming in; this system is widespread in the U.S.A. where B17s and even Stratocruisers are used backed by smaller aircraft.

The aircraft requirements which are considered desirable are in the main very similar to those published as an American specification for a general purpose agricultural aircraft, the essentials of which are condensed in the Appendix. There are different schools of thought on what features should be accented; for instance, some prefer to emphasise controllability, others climb performance, others structural robustness. The Department of Civil Aviation's prime concern is that the aircraft's performance should not be below a well-defined minimum, this being specified in the form that the minimum take-off climb gradient shall not be less than 10 per cent under I.S.A. sea level conditions, or 6 per cent under ambient temperature conditions.

The broad aim of American Regulations is to make regulations as elastic as possible consistent with safety of the third party. For example, provided an aircraft is not operated over built-up areas, it can be flown at any all-up weight which the aircraft can maintain in flight. Further, any aircraft modification could be made provided it is with the concurrence of an authorised officer of the Civil Airworthiness Authority and suitable automobile parts can be used unreservedly.

A similar approach but on a much more rational airworthy basis is being pursued in Australia, *e.g.* take-off weights in excess of the normally certified weights are permitted and certain automotive parts and equipment are permitted.

APPENDIX

1. PERFORMANCE
   - (*i*) Useful load of 30 to 40 per cent of gross weight.
   - (*ii*) Capable of take-off at full load from unpaved ground and reaching 50 feet within 1,320 feet under standard conditions.
   - (*iii*) Minimum safe flying speed 45 m.p.h. and range of operating speed while applying materials to be 60 to 100 m.p.h.
   - (*iv*) Engine cooling system to be ample for high temperature operating conditions.
   - (*v*) Minimum take-off climb gradient shall not be less than 10 per cent under I.S.A. sea level conditions, or 6 per cent under ambient temperature conditions.

2. CONTROLLABILITY
   - (*i*) Control forces to be light to prevent pilot fatigue as controls are used continuously.
   - (*ii*) Rapid aileron control, comparable with fighter effectiveness ($pb/2v=0{\cdot}12$ min.).
   - (*iii*) Lateral stability such that in a flat skidding turn at stalling speed, aeroplane will not spin.

3. VIEW
   - (*i*) Excellent view forward and down required for low altitude flying.
   - (*ii*) Clear view in direction of turning. A low-wing monoplane is the best configuration.
   - (*iii*) Clear view to rear to see trail being laid.
   - (*iv*) Good view in taxying for working on unprepared landing fields.

4. CRASH PROTECTION
   - (*i*) Fuselage and cabin design to resist nominal crash loads, and structures designed to absorb energy by progressive collapse. Structure should bend and fail outwardly.
   - (*ii*) Pilot and passengers' seats located as far aft as possible.
   - (*iii*) Fuel tanks in wings, NOT in fuselage.
   - (*iv*) Instrument panel designed to be free of sharp edges, to have energy absorbing shields and to be on shear pins and capable of forward displacement.
   - (*v*) Safety harness and seats strong enough to resist failure up to point of cabin collapse.

5. LOADING
   - (*i*) Hopper door located for easy loading by hand or machine, and tightly sealed when closed.
   - (*ii*) Provision for quick change from dusting to spraying.

6. MAINTENANCE
   - (*i*) Simple, rugged construction.
   - (*ii*) All control linkages and critical parts easily inspected. All parts which need servicing easy to remove and replace.
   - (*iii*) Propellers easily repairable after minor accidents. Solid aluminium propellers are excellent in this respect.
   - (*iv*) Structure capable of being easily cleaned and should be protected from chemical corrosion.
   - (*v*) Engine well protected from dust by proper location of carburettor inlet, ample air filters and full-flow oil filters.

The Operational Requirements of Aircraft

With Special Reference to the Possible Application of V.T.O.L. and S.T.O.L. Aircraft in Africa South of the Sahara

by

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1. Introduction

There is no doubt that there is a very definite requirement for V.T.O.L. and S.T.O.L. aircraft in Southern Africa. With the increasing tempo of development of the various territories, South of the Sahara, the need for S.T.O.L. and V.T.O.L. aircraft will increase rapidly. The aim of this paper is to point out a number of the requirements and to draw attention to some of the problems to be overcome, in connection with the application of such aircraft.

2. Functions of Aircraft in Africa

Statistical data[1] referring to the areas, population densities and surface transport facilities of some of the African territories South of the Sahara, are given in Table I. As far as transportation facilities reflect the degree of development, it is clear that most of these territories are in a relatively underdeveloped state. In recent years, however, there has been an increasing rate of economic expansion in Africa, and with it a growing need for aircraft facilities. Apart from the usual applications, such as for passenger and freight transportation, there are duties, as follows, which are of special importance in Africa.

2.1. POLICE AND MILITARY ACTION

The use of V.T.O.L. and S.T.O.L. aircraft for police work, and for military operations, assumes greater importance in Africa than in practically any other part of the world. Due to the long distances involved and the smallness of the Police forces, it is becoming difficult to maintain proper Police control in many African territories without the use of airborne forces, while, in particular, it is often required to operate over terrain where air-to-ground contact cannot be maintained without the use of V.T.O.L. aircraft. The value of helicopters in guerilla warfare has already been proved under conditions similar to those existing in large parts of Africa, but the advent of V.T.O.L. aircraft capable of higher speeds would significantly increase the effectiveness of this type of operation.

Naval operations such as anti-submarine action, harbour defence, rescue and towing, also fall within the scope of V.T.O.L. aircraft. Due to a lack of aircraft carriers and a shortage of coastal aerodromes, certain coastal defence operations cannot be effectively carried out by means of conventional aircraft.

2.2. SURVEY AND CONSTRUCTIONAL WORK

Extensive use is being made, in various parts of the world, of helicopters for constructional and survey work, and there is a vast scope for this type of application in Africa. It has been reported[2] that time-savings of up to 99 per cent were achieved during the development of the Aluminium Company of Canada's hydro-electric power project in Northwest Canada, when equipment such as cement mixers and aluminium tower sections were transported without difficulty to destinations in inaccessible mountain regions. This ability of V.T.O.L. aircraft to carry freight without the impediment of the usual restrictions on cargo space is an important factor in their favour, and so is their ability to deliver cargo at the exact destination point, and to pick up and deliver cargo without outside

TABLE I

Territory	*Area* sq. miles	*Population* per sq. mile	*Miles of navigable road* per sq. mile	*Miles of railway* per sq. mile
Angola	481,351	9·6	0·045	0·003
Basutoland	11,716	47·5		
Bechuanaland	275,000	1·1		
Belgian Congo	925,907	16·2	0·017	0·003
Ethiopia	409,266	24·4		
French Cameroons	166,795	18·0		
French Equatorial Africa	965,250	4·5	0·022	0·003
Ghana	91,843	44·9		
Kenya	224,960	24·2	0·075	0·007
Mozambique	297,731	21·5	0·060	0·005
Nigeria	372,674	67·1	0·067	0·005
Nyasaland	47,949	51·3	0·080	0·006
Rhodesian Federation	435,072	19·3	0·045	0·008
Somaliland	274,447	19·0		
South West Africa	317,725	1·2		
Sudan	967,500	8·6		
Swaziland	6,705	28·9		
Tanganyika	342,706	21·9		
Union of South Africa	472,494	25·6	0·190	0·025

Received 27th September 1959.

assistance. There are many areas in Africa where existing means of transport are impractical, impossible or inadequate, and where constructional work for mines, dams, bridges, power lines, telephone lines, pipelines and so on can also be done more economically or made possible, or greatly augmented, by the use of V.T.O.L. or S.T.O.L. aircraft. Furthermore, by fitting V.T.O.L. aircraft with electronic survey apparatus, they could offer a convenient means of prospecting for minerals and oil in the previously unexplored regions of Africa, while survey work for roads, railways, irrigation schemes, and so on, can often be done more economically from the air, especially in underdeveloped areas.

2.3. PEST AND DISEASE CONTROL

The most important application of aircraft in agriculture is that of pest control, and in this respect the aircraft is becoming an indispensable tool in the development of African territories where a large percentage of the yearly crop losses is due to the ravages of a great variety of plant diseases and pests. It must also be realised that some regions are only habitable by virtue of the control of the carriers of malaria, sleeping sickness (encephalitis lethargica) and other tropical and subtropical diseases. It is estimated that in some areas more than 90 per cent of the native population suffer from bilharzia, and the eradication of this disease would tremendously increase the productivity of the affected areas. The success of disease control from the air has already been proved in various parts of Africa, notably in South Africa where conditions in the lower lying subtropical regions have been made safe for human habitation and stock raising by the extensive eradication of malaria mosquitos and tsetse fly.

The most efficient method of locust control lies in the location of the breeding areas, where the insects may be destroyed before they commence on their devastating mass migrations. In some parts of Africa the time-consuming procedure of tracking down the breeding areas on foot and by means of surface transport is still being used. This type of operation could, however, be performed with much greater efficiency, and perhaps economy, by means of helicopters or other more suitable V.T.O.L. or S.T.O.L. aircraft. (In the Argentine the eradication of locust hordes by dusting from helicopters has been achieved with an effectiveness of 98 per cent.) Other pests, such as army worm, may be controlled from the air, and in South Africa, where extensive crop damage is caused each year by large flocks of finches, the location and destruction of these birds by using aircraft is already proving successful.

As far as crop spraying and dusting is concerned, the use of V.T.O.L. aircraft has certain very distinct advantages over the use of conventional aircraft. The most obvious of these is that, due to their manoeuvrability, V.T.O.L. aircraft can cover fields which might be, due to difficult topographical features, impossible to spray efficiently with conventional aircraft. Also, in the case of a helicopter, for instance, the rotor downwash, which propels large volumes of air downwards at comparatively low velocity, permits complete coverage of extremely heavy foliage. While conventional aircraft usually dispense the chemicals for the most part over the upper surface of the vegetation, the swirl which is induced in helicopter rotor downwash as it reaches the ground allows a much more thorough coverage to be achieved. This is of importance, for instance, where ground pests are to be destroyed in thickly wooded regions. As far as useful operating time per flying hour is concerned, the use of conventional aircraft for crop spraying and dusting compares very unfavourably with that of V.T.O.L. aircraft, a large proportion of the flying time being absorbed in flying to and from the nearest landing strip for fuelling and the reloading of chemicals. The ability of V.T.O.L. aircraft to reload and refuel from surface vehicles at the site of the fields is of great importance in Africa, where the distance to the nearest airstrip could, in many cases, render crop spraying by conventional aircraft an uneconomical proposition.

Although crop spraying by helicopters offers many advantages over conventional aircraft, their low flying speed, difficult flying characteristics and high cost point to the need for a V.T.O.L. aircraft that is cheaper to make, easier to fly and capable of higher speeds. As soon as such an aircraft becomes commercially available it is almost certain that conventional aircraft will not be able to compete in this field of application.

2.4. PRIVATE OPERATION OF AIRCRAFT

About 43 per cent of all the non-military landing fields in South Africa are privately owned[3]. In so far as these are mostly situated on farms, this figure serves to illustrate the extensive use of aircraft by the farming community. There are approximately 115,000 farms in the Union of South Africa, covering a total area of 215,722,000 acres, which means that an "average" farm size is roughly 1,900 acres[1]. In the cattle grazing areas of the Northern Cape, North Western and Northern Transvaal, however, the average farm size is about 6,000 acres, and in the sheep grazing areas of the North Western and Western Cape, where semi-arid conditions prevail, the average farm size is about 15,000 acres[3]. On these large farms aircraft can fulfil an important rôle, and the nature of the duties involved is such that suitable V.T.O.L. or S.T.O.L. aircraft represent the most practicable answer.

One of the most important applications is crop spraying, and since crop spraying by means of conventional aircraft is known to be a difficult and somewhat hazardous procedure most farmers engage the service of specially equipped organisations for this purpose. Helicopters are usually not within the means of the average farmer, and although crop spraying by helicopter does not, as is the case when using conventional aircraft, require from the pilot any abilities beyond his usual scope, it is doubtful whether any farmer would incur the expense associated with helicopter flying training. Should, however, a V.T.O.L. aircraft become available, which is relatively easy to fly and within the means of private owners, it is certain that such a craft would prove to be a considerable asset to farmers. Fields which are too small to justify the engagement of

a crop spraying undertaking, or which are likely to suffer damage through ground spraying apparatus, could then be sprayed frequently and effectively from the air by the farmer.

Untimely frosts may cause considerable damage to crops, and freak frost conditions have resulted in entire crops of subtropical fruit being destroyed. In marginal areas, where the degree of frost is not too high, V.T.O.L. aircraft may be used to provide protection against frost. This is achieved by flying at low speed through an upper stratum of warmer air, the rotor downwash forcing the warm air blanket into the cold lower strata, causing the ground temperature to be raised to a safe level. Helicopters have been used for this purpose with good results, but at somewhat high cost, and the use of private aircraft would dispense with the overhead costs involved in hiring an aircraft.

Other duties such as inspecting, seeding and cattle herding would fall well within the scope of V.T.O.L. or S.T.O.L. aircraft.

2.5. FIRE FIGHTING AND CONTROL

As in Australia, large parts of Africa are subjected to long, dry winter periods, the attendant danger of bush and veld fires constituting an annual threat to timber, crops, stock, game, and even human, safety. The manoeuvrability of V.T.O.L. aircraft make them especially suited for fire-spotting duties, but apart from fire-spotting, which is only economically tenable in afforestation areas (a total, in South Africa only, of almost 3,000,000 acres, mostly in mountainous regions[6]), suitable V.T.O.L. aircraft might offer a convenient means of fighting fires in areas having natural forest or bush vegetation. This would require aircraft with a high payload capacity to cope with the water containers and pumping equipment.

2.6. GAME CONTROL AND SURVEYS

There is a continual danger in Africa of foot-and-mouth disease being spread through the movement of game. Also, in some regions crop damage results from the straying of elephant and other big game onto farms in the vicinity of the numerous game reserves all over Africa. The use of V.T.O.L. aircraft provides a convenient and effective means of controlling the movement of this game.

Aircraft have also been used, in game preservation areas, for game counting purposes, and in this respect the requirement is usually for an aircraft capable of low speeds and silent operation. This, and other game warding duties such as the control of poaching and the hunting of dangerous man-killers fall well within the scope of suitable V.T.O.L. or S.T.O.L. aircraft.

2.7. OTHER APPLICATIONS

In addition to the applications mentioned, there are many duties which are so well known and for which the effectiveness of existing V.T.O.L. and S.T.O.L. aircraft have been so conclusively proven, that they need hardly be mentioned. The suitability of these aircraft for duties such as emergency relief in case of floods and other disasters, search and rescue work, reconnaissance and postal duties, does, however, assume special importance in Africa where the inaccessibility of some of the regions and the sparseness of aerodromes often preclude the possibility of using conventional aircraft. Once V.T.O.L. aircraft have been developed to a stage which would justify their extensive application it is certain that a wide range of additional duties, which are at present being performed by more cumbersome means, would also be brought within their scope.

3. Factors Affecting the Operational Requirements of V.T.O.L. and S.T.O.L. Aircraft

3.1. SIZE OF AREAS

Due to the sizes of the areas involved (*see* Table I) and the relatively underdeveloped state of most of the regions, long distances have to be flown without refuelling. Since, in their present state of development, the range of V.T.O.L. aircraft falls considerably below that of conventional fixed-wing aircraft, special attention will have to be given to increasing the range of V.T.O.L and S.T.O.L. aircraft which are to be used for flying cross-country. As a general specification a range of, say, 300 miles might be necessary. This may, of course, be achieved by the use of special long-range fuel tanks, the only disadvantage being the associated sacrifice in payload. As far as transportation over long distance is concerned it is doubtful whether V.T.O.L. and even S.T.O.L. aircraft can compete with conventional aircraft. It is, however, conceivable that, especially in Africa, V.T.O.L. and S.T.O.L. aircraft may be required to fly long distances in order to carry out duties beyond the scope of conventional aircraft, and it is for this reason that the development of long-range V.T.O.L. aircraft is desirable. Although helicopters have already flown long distances with the aid of additional fuel tanks[7], because of its low speed it is not the ideal machine for this type of undertaking, and it might, in this respect, be replaced with advantage by V.T.O.L. aircraft of the tilt-wing or ducted fan type.

3.2. LANDING SITES

The number and distribution of aerodromes constitute an important factor in determining the effectiveness with which conventional aircraft may be used for any given duty. Fig. 1 shows the distribution of landing fields, excluding military ones, in the Union of South Africa, South West Africa, and the British protectorates[8]. There are a total of about 280 public and private landing fields in these territories, this representing on the average about one landing field per 3,800 square miles. This figure, which corresponds to approximately 13 landing fields in an area the size of England, illustrates a present limitation imposed on the use of conventional aircraft in Africa. In territories such as South West Africa and Bechuanaland the airfield density is much lower (*see* Fig. 1), and operations such as locust control by means of spraying from conventional aircraft would require either a large amount

TABLE II

LENGTHS OF RUNWAY (LONGEST RUN) OF LANDING FIELDS (PUBLIC AND PRIVATE) IN SOUTH AFRICA, SOUTH WEST AFRICA AND THE BRITISH PROTECTORATES

Length (ft.)	1000 to 2000	2000 to 3000	3000 to 4000	4000 to 5000	5000 to 6000	6000 to 7000	*Over* 7000
Frequency per cent	4·2	26·0	36·3	18·3	7·4	6·0	1·8

of unproductive flying to and from the nearest landing field, or the construction of temporary landing strips near the operation site. Both these alternatives would incur large and possibly prohibitive expense.

Of the 280 landing fields shown in Fig. 1, 43 per cent are privately owned, and by far the greatest proportion of these do not have fuelling and servicing facilities. As far as maximum length of runway (*see* Table II) and radio communication facilities are concerned, the greatest proportion of landing fields would not be able to accommodate the larger aircraft which would be required for say, military operations, except if they were of the S.T.O.L. variety.

The lack of fuelling facilities introduces an important functional requirement for aircraft in Africa, for while it is usually possible to obtain ordinary low octane fuel or paraffin within a reasonable distance from any given point, the supply of high octane fuel is mostly limited to certain highly developed regions. In this respect, therefore, aircraft equipped with gas turbine engines would show a distinct advantage over high compression piston-engined aircraft, and since there are at present no fixed-wing gas turbine aircraft available which are capable of operating economically at the low speeds necessary for crop spraying, survey and similar duties, the use of V.T.O.L. aircraft having gas turbine engines might prove useful for operation in the more remote regions of Africa. This particular advantage attached to V.T.O.L. aircraft is, of course, somewhat offset by the larger specific fuel consumption that goes with this type of aircraft-engine combination.

3.3. VEGETATION AND TOPOGRAPHY

In Southern Africa the greater proportion of the Northwestern region (Northwest Cape, South West Africa and Bechuanaland) is desert or semi-desert, going over to the Karoo Plateau in the South, the High Veld in the East and the Central African Savanna in the North. The vegetation in the extreme Eastern and North Eastern regions consists largely of woodland, bushveld and shrub. As far as vegetation is concerned these latter regions are the only ones that would present difficulty for V.T.O.L. and S.T.O.L. aircraft.

The main mountain ranges are along the escarpment which separates the narrow coastal plain from the great interior plateau. The British Protectorate of Basutoland is extremely mountainous, and in this territory, for which considerable economic development is being planned, the application of V.T.O.L. or S.T.O.L. aircraft should find a wide scope.

3.4. ALTITUDE AND TEMPERATURE

The combination of extremes in temperature and altitude in various parts of Africa poses a difficult performance problem, especially with regard to VTOL aircraft. Ability to operate effectively at pressures corresponding to ground level altitudes of up to 8,000 ft. and more

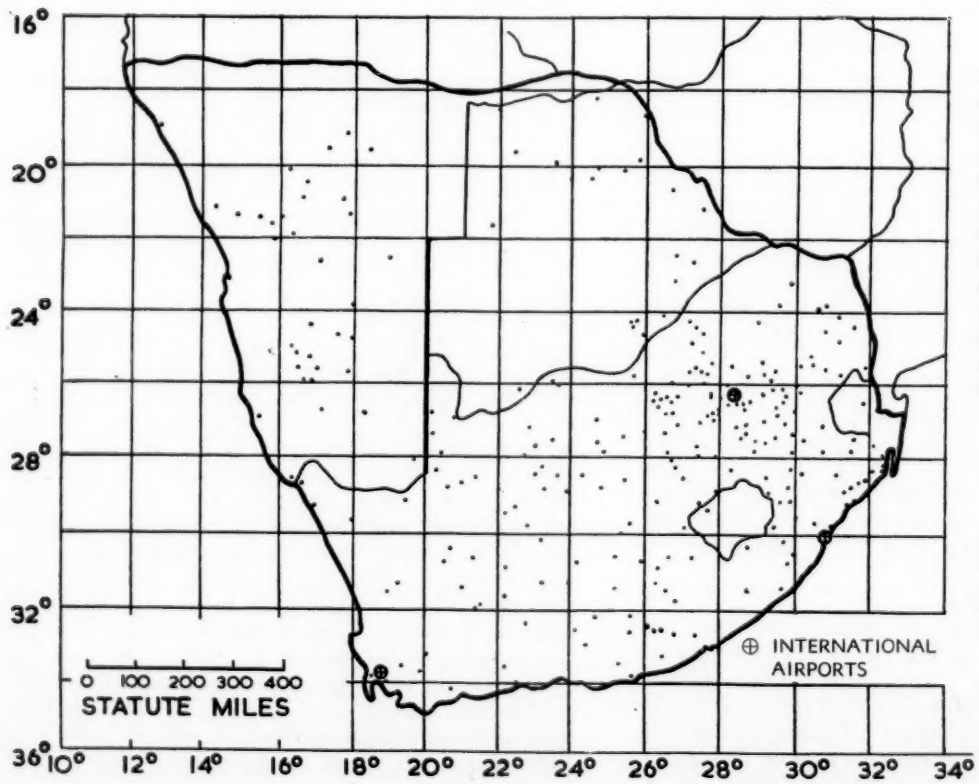

FIGURE 1. Union of South Africa, South West Africa and British Protectorates. Distribution of public and private landing fields.

would be a prerequisite for the use of such aircraft in Africa, and the minimum required ceiling would have to be of the order of 12,000 ft.

Elevation contours for Southern Africa are shown in Fig. 2, from which may be seen that most of the territory lies above 3,000 ft., while a significant proportion lies between 4,000 and 6,000 ft. The altitudes above sea level of the landing fields shown in Fig. 1 are tabulated, on a frequency basis, in Table III.

In Figs. 3 and 4 the mean temperatures for the coldest and hottest months (July and January respectively) are plotted. Considerable deviations from the mean are possible, and aircraft may in some cases be required to operate under conditions varying between several degrees of frost, to well above 100°F. If the aircraft are fitted with efficient oil cooling systems the only problem posed by high temperatures is that of power reductions, so that a sufficient margin would have to be allowed in engine power. The tendency to prefer twin-engined V.T.O.L. designs in order to ensure safe landing from all altitudes in case of engine failure implies a considerable reserve in power, so that such aircraft may be ideally suited for operation under stringent temperature and altitude conditions. Also, since the performance of gas turbine engines is less sensitive to reductions in air density than is the case with piston engines, turbine-engined V.T.O.L. and S.T.O.L. aircraft would be the better suited to conditions in Africa.

As a further point it may be mentioned that large ground-to-air temperature gradients may occur in the arid regions. One effect of the consequent existence of layers of denser air at ground level is the well-known mirage phenomenon, which may at times render the horizon indistinct and cause orientation difficulties, especially in the case of V.T.O.L. aircraft.

TABLE III

ALTITUDES ABOVE SEA LEVEL FOR LANDING FIELDS (PUBLIC AND PRIVATE) IN SOUTH AFRICA, SOUTH WEST AFRICA AND THE BRITISH PROTECTORATES

Altitude (ft.)	0 to 1000	1000 to 2000	2000 to 3000	3000 to 4000	4000 to 5000	5000 to 6000	6000 to 7000
Frequency per cent	12·7	6·3	9·5	24·3	30·3	15·8	1·1

3.5. WEATHER CONDITIONS

Most of the subtropical and temperate regions of Africa are subjected to seasonal rains extending over 3 to 5 months in summer, with dry winter periods. Dusty conditions are therefore not restricted to the arid regions, and may prevail during a large part of the year. Apart from the danger of dust storms during operation in desert or semi-desert regions, the main dust hazard will be encountered during take-off, hovering near ground level, and landing, and may seriously affect the durability and serviceability of engines and all exposed mechanisms.

High rainfalls, concentrated over short periods, sometimes render landing strips unsuitable for use by conventional aircraft, and during these periods V.T.O.L. aircraft may become the only means of air transport. However, some parts of Africa are prone to violent thunderstorms and heavy hail, making flying hazardous for all types of aircraft incapable of high altitudes.

As far as wind conditions are concerned, difficulties are sometimes experienced due to gustiness along the escarpment, so that the inherent instability of such V.T.O.L. aircraft as the helicopter may render it difficult to operate near ground level. Along the coast from Port Elizabeth to Cape Town difficult flying conditions prevail due to strong south westerly winds which cause extremely turbulent conditions over the mountains. Flying heights of about 1,500 ft. above the mountains are necessary, and the landing of V.T.O.L. aircraft would be hazardous. On the inland plateau maximum gusts of the order of 80 m.p.h. can be expected.

4. Conclusions

There seems to be no doubt that the future will see an enormous increase in the application of V.T.O.L.

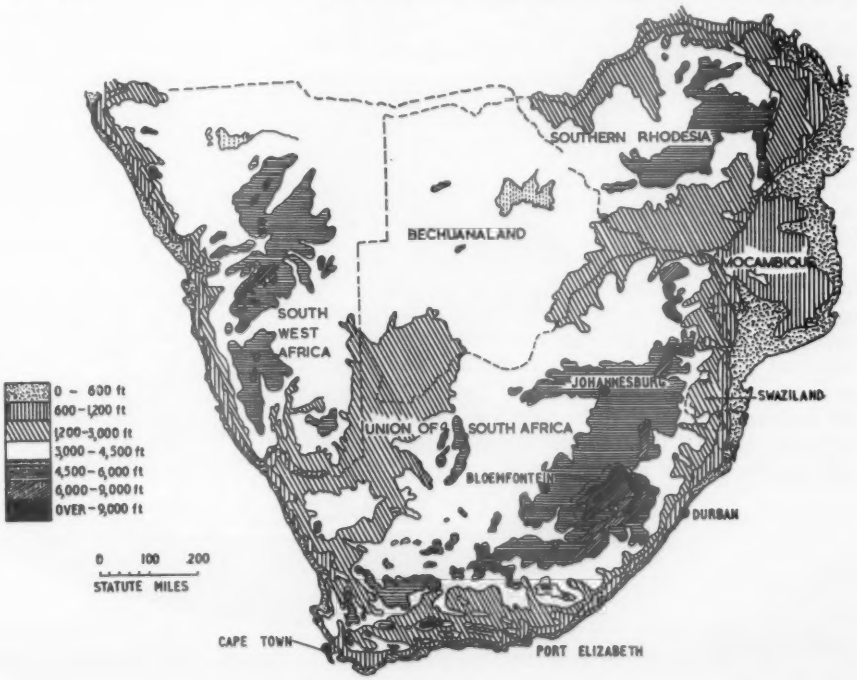

FIGURE 2. Southern Africa—elevation.

FIGURE 3 (*left*). Union of South Africa. Mean temperature (°F) for July.

FIGURE 4 (*below*). Union of South Africa. Mean temperature (°F) for January.

and S.T.O.L. aircraft. Not only will these aircraft be required for duty in the developed territories of Africa, but their functional characteristics also render them eminently suitable for the task of assisting in the development of underdeveloped territories. The only commercially available member of the V.T.O.L. family is at present the helicopter, and although it has been brought to a refined state of development due to the increasing demand for this type of aircraft, it nevertheless suffers from certain inherent disadvantages which make it unsuitable for a large number of applications. The foremost among these disadvantages are the high cost of manufacture, the exacting maintenance requirements, the difficult flying characteristics and consequent high cost of pilot training, and low speed. It seems, furthermore, that especially as regards cost of manufacture, there is not much likelihood of the helicopter being brought to within the means of the private owner. There are, however, a number of V.T.O.L. and S.T.O.L. aircraft, as yet in the development stage, which show promise for the future.

Investigations into various designs such as ducted fans, tilt-wing aircraft and coleopters have been commenced in most parts of the world, and there are indications that the difficulties associated with the conventional helicopter are not insurmountable. It is realised, however, that the special nature of some of the problems that have to be solved in the evolution of V.T.O.L. and S.T.O.L. aircraft for duty in Africa will still require further research.

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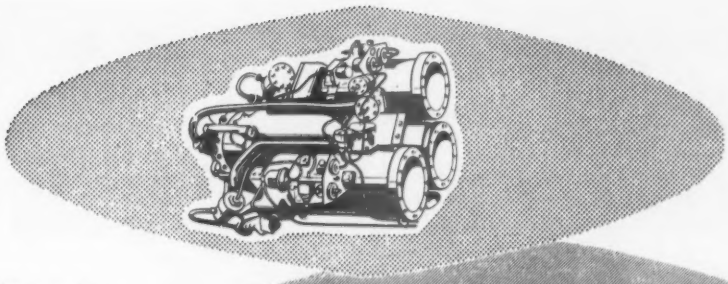

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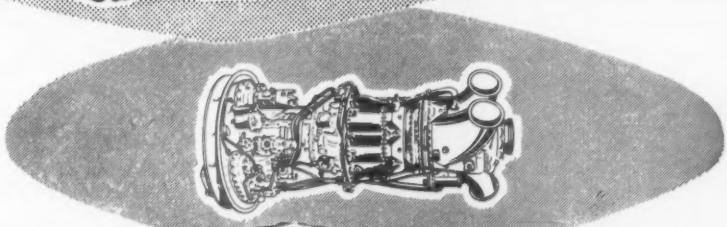

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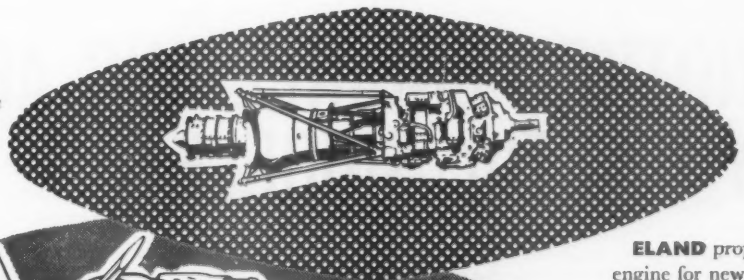

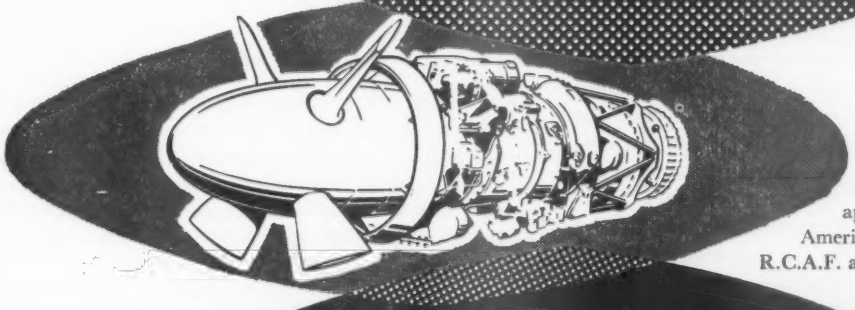

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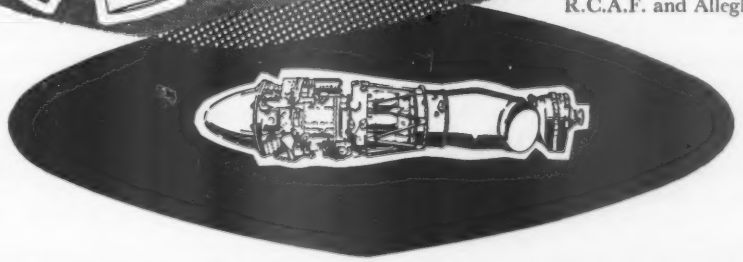

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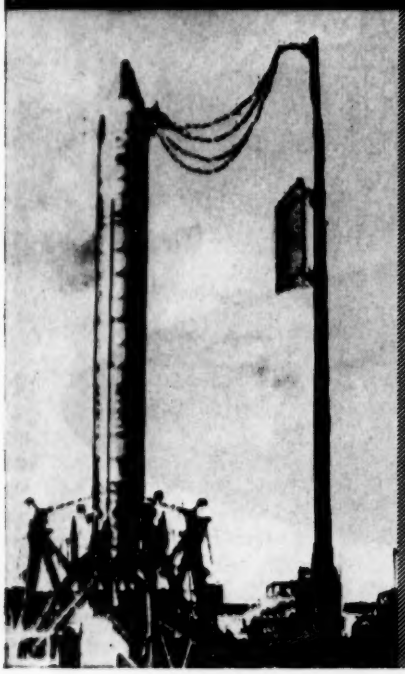

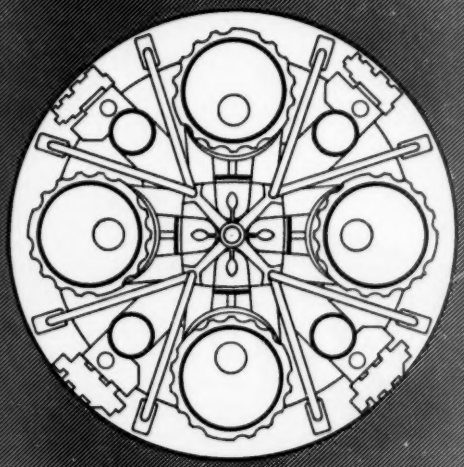

End view showing combustion chambers which can be inclined for vehicle guidance.

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Problems of Interplanetary Navigation and Atmospheric Re-Entry*

by

T. R. F. NONWEILER, B.Sc., A.F.R.Ae.S., A.F.I.A.S.

(Department of Aeronautical Engineering, Queen's University, Belfast)

IN THIS LECTURE I want to survey some of the problems of the aerodynamics of re-entry, as they affect either purely earth-bound or space vehicles; and in particular, as they are affected by the trajectory the vehicles are designed to follow, or may find themselves upon due to some error of navigation. This is a self-set task and an ambitious one: but in truth it is an artful one, as it provides an excuse for me to leave the discussion of problems at a stage where their difficulties begin to defeat me.

1. The Estimation of Heat Transfer

The critical problems of re-entry are primarily concerned with the retardation and the heat transfer suffered and of these the latter is no doubt by far the more difficult to assess with accuracy, and it would seem proper before going further to mention what these difficulties are. First and foremost the question arises in a theoretical assessment whether it is proper to assume the state of flow in the boundary layer to be laminar or turbulent unless, of course, it is separated, when it has been usual to treat the heat transfer as negligible, though it is now becoming more apparent that this is not always justifiable. However, in the high Mach number conditions in which doubt arises, it often happens that, despite a high Reynolds number, judged at least by ordinary standards, the theoretical prediction of skin friction is lower for turbulent than laminar flow (Fig. 1). This is because theory shows a more rapid drop of friction with Mach number for the turbulent layer. Such a result is incompatible with our concept of the action of turbulent mixing, and this either means that the turbulent flow friction is wrongly predicted (which may well be so, as the prediction is basically an extrapolation) or that laminar flow must exist. But theory in these instances can at least provide no more pessimistic prediction of heat transfer than that for the laminar flow boundary layer, in which we may place as much hope as its assumptions justify.

In other instances where the Mach number of flight is high, it may be that the existence of strong shock waves reduces the Mach number of the flow outside the boundary layer to familiar proportions, so that the state of the boundary layer flow can be decided with reasonable certainty. But whether or not this is so, there is always some question about the effects of dissociation or recombination upon the flow, and upon the magnitude of the transport quantities. Even if the flow behaviour can be established in the conditions of frozen equilibrium or thermodynamic equilibrium, one is aware that the true condition may be intermediate between the two. In most conditions of interest, however, the time of immersion of particles within the boundary layer is sufficiently long for thermodynamic equilibrium to exist (Fig. 2). Where it is not, reactions outside the boundary layer will certainly not be in thermodynamic equilibrium either.

Fortunately, in most examples which have been worked, the effect of the presence of reactions on the rate of heat transfer to the surface is not severe. Certainly a more important effect, which introduces great complications if it is not ignored, is that of the self-induced pressure gradient. But broadly speaking this seems to re-distribute the heat transferred to the body, alleviating the heating close to the nose and increasing it aft, without adding greatly to the total quantity transferred. Thus, in so far as accentuated heating near the nose is an embarrassment in design, the self-induced pressure field can be said to be a beneficial effect.

Another doubt attaches itself to the importance of

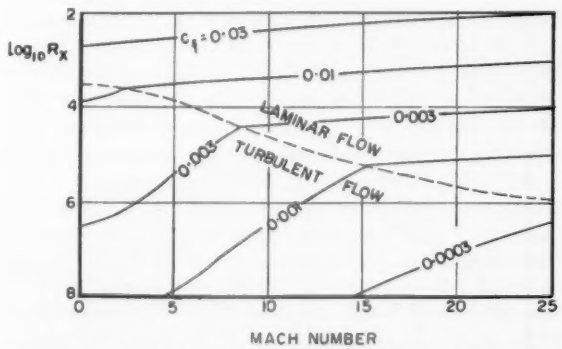

FIGURE 1. As Mach number increases, the skin friction drag and heat transfer coefficients reduce, and this reduction is more rapid for the turbulent than the laminar flow boundary layer. Thus the Reynolds number below which laminar flow values exceed turbulent flow values also increases with Mach number. This figure shows skin friction coefficient (calculated on intermediate enthalpy theory) for a cold flat plate.

*The tenth lecture given before the Astronautics and Guided Flight Section—on 22nd October 1959.

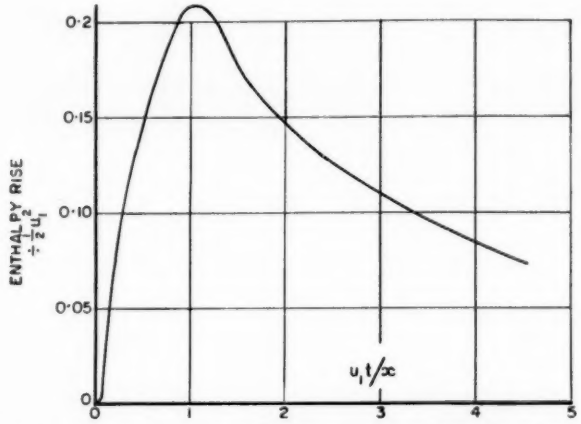

FIGURE 2. Time taken (t) for particle of air to heat up after passing into a laminar boundary layer over a cold flat plate at high speeds (u_1 = free stream speed, x = distance of particle from nose).

the heat radiated from the gas to the surface. The boundary layer plays no important part in this process, and only when the external flow is heated by its passage through an intense shock does this problem assume importance; and then indeed only when there are appreciable quantities of water vapour or carbon dioxide present in the atmosphere. At temperatures below that needed for dissociation to be present, it would appear that such radiation as exists is too small to be of interest, but in the presence of dissociation, particularly in a system which is not in thermodynamic equilibrium, there is no engineering basis for judging its proportions.

Slip flow effects are yet another complication, but once again, in practice it is usually found that they are quite unimportant during that part of a re-entry in which the rate of heating is greatest (Fig. 3), and in any event they tend to reduce the rate of aerodynamic heating. The fairest summary that can be made, in fact, is that the neglect of many of these complications results in a pessimistic assessment of heat transfer rates, and no large errors in the theoretical predictions are anticipated. Only of course where skin friction is an important contribution to the total drag are the same doubts attached to estimates of the drag, and through it to estimates of retardation.

2. Methods of Surface Cooling

What errors in calculating the rates of heating there may be are more important in applications where the body temperature is controlled primarily by the absorption of heat into its surface than by radiation cooling; in the one instance body temperature depends primarily on the total quantity of heat transferred, and in the other on the fourth root of the instantaneous *rate* of heating. By absorption we here mean the use of conducting material of high heat capacity to store the heat transferred: beryllium is an obvious example of this. There is a third class of cooling methods depending upon the absorption by insulation material, where the exposed surface temperature is controlled by change in state of the material, and one might include in this category the methods of liquid cooling, which are well known.

Yet another class of cooling methods involves mass-transfer—that is, the injection into the boundary layer of air or other gas, so as to alter its characteristics and reduce the rates of heat transfer: this would usually be associated with a need to preserve the surface condition, as it might be porous, and so absorption of the reduced heat input by conducting material, or radiation cooling, would be a necessary accessory. It is, in fact, particularly suited to the latter as the modification to the boundary layer is most emphasised near the nose where *rates* of heating are greatest, but a considerable mass transfer is needed to affect significantly the total heat transfer over the complete surface.

Again it is evident from a study of magneto-aerodynamics, that considerable modification of heat transfer rates, particularly the nose, can be obtained from the action of a generated magnetic field on ionised air. But neither of these techniques aimed at changing the boundary layer behaviour is as yet well developed, and as beryllium is still an uncommon structural material (and an expensive one), present day choice lies between liquid cooling or ablation methods, and radiation cooling pure and simple. The liquid cooling method is more complicated but necessary in non-expendable structures, while the simplicity of ablation otherwise

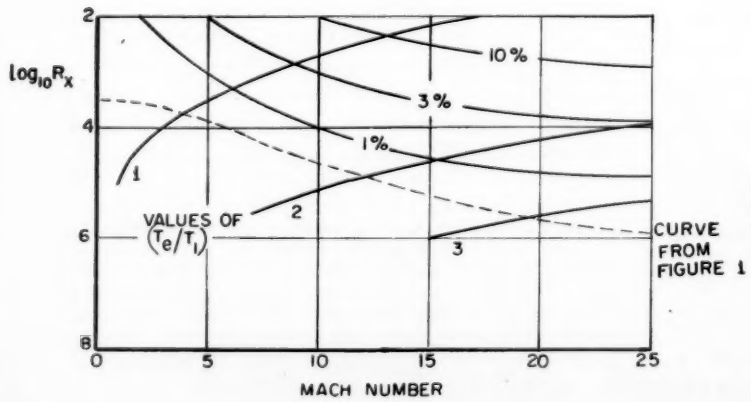

FIGURE 3. Percentage change in heat transfer coefficient due to slip-flow effects for various Mach numbers, and radiation equilibrium temperatures (T_e) for a laminar boundary layer one foot from nose of flat plate (T_1 = free stream temperature).

recommends itself. Radiation cooling is of course a relevant alternative for either expendable or non-expendable structures, and where the role demands heat transfer rates which do not involve prohibitive surface temperatures it would obviously be preferred. It is often only possible to keep heat transfer rates low enough to permit the use of known structural materials, by introducing a special modification to the flight plan. Satellite re-entry is an example of this, where only by using very low density ballistic re-entry vehicles can radiation equilibrium temperatures be kept just within the working range of steel.

3. Long-range Missiles—Ballistic

Both heating rates and retardation reach much higher values on re-entry of the I.C.B.M. than the satellite (Fig. 4). Over ranges of the order of 2,000-9,000 miles, ballistic missile re-entry involves retardations of more than 50g, compared with 8g for a ballistic satellite re-entry. Over the same range peak heating rates likewise exceed that in a satellite re-entry, being about twice as large for missiles covering ranges of 5,000-9,000 miles. Thus if radiation cooling is marginal for a satellite, involving temperatures of about 1,000°C, it may well be out of the question for ballistic missiles.

This reasoning suggests why ablation cooling has become the common method for I.C.B.M. re-entry heads. On the other hand the problem of ablation is critically dependent on the total heat transferred, and this in turn is some particular fraction of the total kinetic energy destroyed in re-entry. Thus ablation or indeed any other form of absorption cooling is more difficult for the ballistic satellite than the slower speed I.C.B.M., which is yet another reason why the case for radiation cooling may be much stronger for satellites.

Control of the total heat input, in ablation cooling, may be effected by reducing the kinetic energy destroyed in re-entry, and that is, by arranging a high speed impact. This may not always be desirable, to say the least! But where it might be an advantage (perhaps in military applications), it is nevertheless difficult to contrive, demanding (weight/frontal area) ratios greatly in

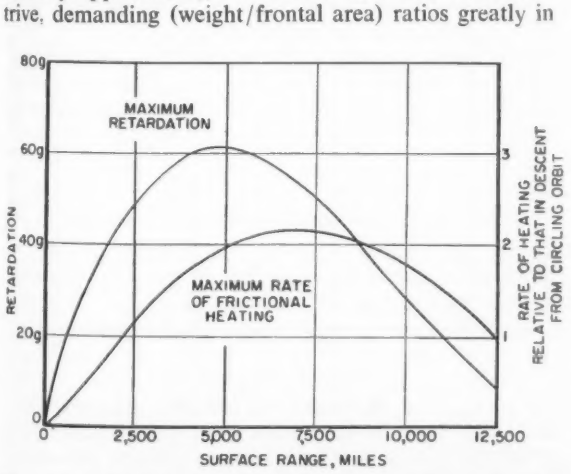

FIGURE 4. Peak levels of retardation and rates of heating during descent of a ballistic missile.

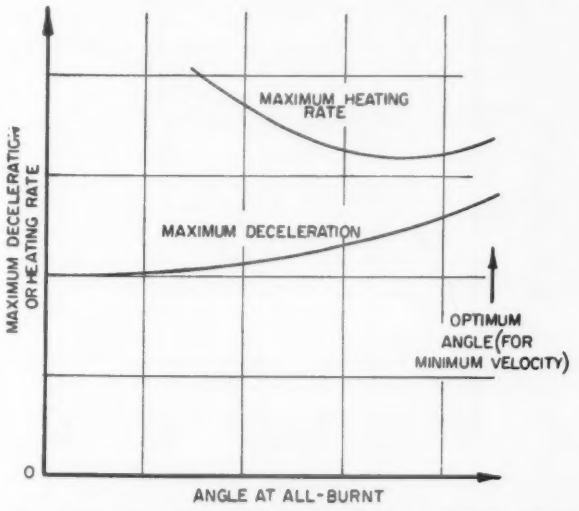

FIGURE 5. Effect of lowering the trajectory of a ballistic missile.

excess of 2,000 lb./ft.^{2}. This figure depends on the drag coefficient of the head, which obviously should be small. But this means inevitably making friction a large component of the total drag, and it is indeed this ratio which is proportional to the fraction of the total kinetic energy destroyed which appears as heat input. Thus there is here a conflict of aims, since this fraction also needs to be kept low.

Due to its weight penalty, ballast would be an unacceptable solution of this dilemma, and one is faced with the straight choice of accepting as heat most of a small loss in kinetic energy, or instead (by making the head have a high wave drag) a small proportion of a large loss in kinetic energy. In fact, of course, the choice between the extremes is likely to be made at the compulsion of reasons quite divorced from aerodynamics.

In the low impact speed descent, it still pays to use a fairly high frontal loading, with the object of avoiding low Reynolds numbers and excessive values of skin friction coefficient. Ideally one would like to make the loading as large as one dared without introducing turbulence, but such a nicety of judgment is more than can at present be exercised.

Some reduction in the rate of heat transfer and the value of retardation can be obtained in trajectories which are faster but shallower than those giving maximum range for a given all-burnt speed (Fig. 5), but such a device generally increases the total heat transferred and so is of no value if absorption cooling is used. This increase is due, for the most part, to the increased kinetic energy, but also to some extent to the fact that deceleration occurs at a higher altitude in a more shallow descent.

4. Long-range Missiles—Winged

Still thinking in terms of long-range rockets, a more severe and important modification is the introduction of lift to produce a steady glide. This only makes

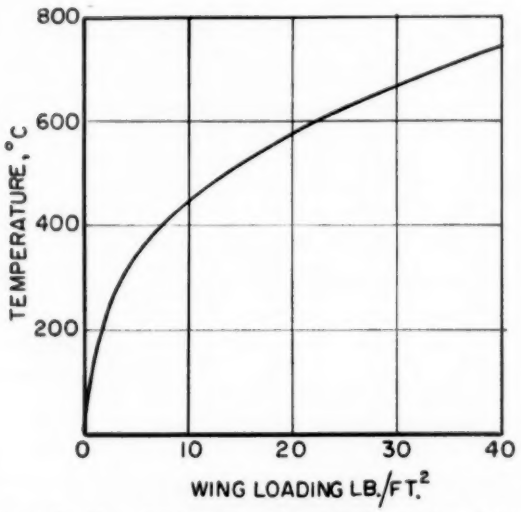

FIGURE 6. Mean temperature over underside of wing of length 30 ft., in level flight at speed of 15,000 ft./sec.

sense, however, if radiation cooling is used, because if the object is to achieve range then a high (L/D) is of paramount importance, and this implies that the aircraft drag coefficient should be low (and also means operating at low C_L). Thus a considerable fraction of the lost kinetic energy is bound to be transferred as heat to the wing. In such a context reduction of vehicle wing loading is the obvious way of controlling surface temperature (Fig. 6) and fortunately this of itself has no great effect upon range. This can be looked upon as arising because there is a greater area from which to radiate the energy which has to be transferred, or because the rate of heating depends on surface pressure which is obviously less if the wing loading is low.

Since the range is not greatly affected, selection of wing loading depends on the right compromise being struck between the increased structure weight of unduly small loading and the weight penalty involved in the choice of materials needed to withstand the radiation equilibrium temperatures. These, of course, are unduly high near the nose, particularly if one envisages the wing as having a sharp leading edge. The use of local heat absorption cooling seems to be fundamentally unsound in such a context, as it is at odds with the whole principle of the use of lift. It is better by far either to sacrifice some drag by rounding the nose and smoothing out the distribution of heat input, or affecting this smoothing out by longitudinal conduction within a locally thickened metallic skin (Fig. 7), which, of course, involves a weight penalty instead of a drag penalty. (In the future, too, mass transfer cooling may offer an acceptable solution.)

We have talked about lift in a steady glide, rather overlooking the unsteady flight plan of the skip-rocket: I do not believe this is now considered to be a serious competitor, because its dips into the atmosphere involve high g and greatly increased heating rates. Admittedly, one might say that if this heat is absorbed it can be radiated during the intermediate ballistic phases, but the absorption material is considerable, unless the skips are very frequent. One is driven in fact towards a steady glide path in the interests of weight reduction. A skip path is, however, an optimum for a winged rocket if range for a given all-burnt velocity is the criterion. Even the trajectory of the glide rocket is greatly improved if there is an initial ballistic arc as, if this is made of the familiar "maximum range" shape, with a dive down into the atmosphere at an angle of 30° or 40°, the range covered in this phase is worth an increase of two in (L/D) in the glide. But the speed loss in the pull-out produces a shortening of the glide

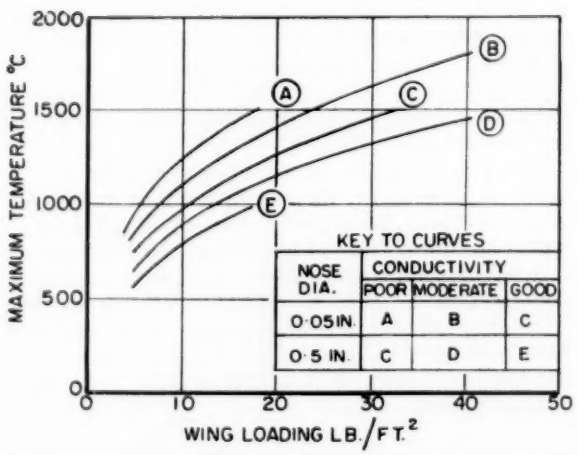

FIGURE 7. Temperature at the uncooled nose of a thin wing in level flight at speed of 15,000 ft./sec. as affected by wing loading, nose diameter and nose material. A typical good conductor is copper; moderate conductors are beryllium, molybdenum or graphite; steel is a poor conductor.

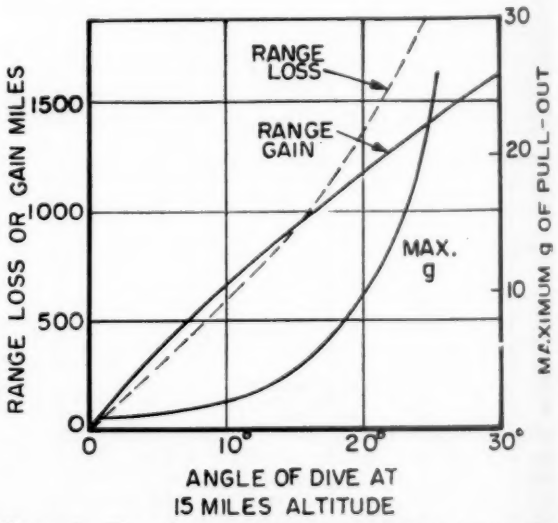

FIGURE 8. The gain in range due to a ballistic trajectory after rocket burn-out at 15,000 ft./sec., and the loss in range in the subsequent glide due to the speed drop in pull-out. The peak values of acceleration needed to pull out from the ballistic trajectory into the glide are also shown.

path which more than nullifies this apparent advantage, and a descent angle of between 10° and 20°, representing perhaps an arc of only half the maximum range, is the usual break-even point (Fig. 8). In fact one would probably design for still shallower arcs as the problems of both heating and stressing are most acute in this initial pull-out manoeuvre.

5. Recovery from a Close Orbit

In the context of recovery of space vehicles, where the range in the glide is no criterion, it is possible to use configurations of smaller (L/D) if this is beneficial, as indeed appears. Fundamentally this involves increasing the height of flight by adopting a high C_L. There is of course some maximum in C_L, generally reckoned to occur around $L/D=1$. The indirect but valuable advantages of high incidence lie in its use as a means of shrouding, and so alleviating the heat transfer to the upper surface; and of allowing an adequate structural thickness of wing as well.

The radiating ballistic shell is another form of re-entry space vehicle which is competitive, as mentioned earlier. In its design, low density is of paramount importance in the reduction of temperature, as is low wing loading for the lifting descent, aided and abetted by a high C_D which like high C_L causes the deceleration to take place where the air is thinner. The absorbing ballistic vehicle on the other hand, though again wanting a high C_D to dissipate its energy in the shock waves to the air at large, is relatively insensitive to its density or loading, except—as mentioned before—that a reasonably high value is desirable to avoid deceleration at low Reynolds number.

It has been my contention that the heat-absorbing ballistic vehicle, the radiating ballistic vehicle, and the radiating winged vehicle all involve much the same weight penalty necessary to ensure safe re-entry from a close orbit, at least if nothing goes wrong with the flight programme. This typically amounts to about half the total load carried. Missing from this list is the heat-absorbing winged vehicle which, however, is out of the running compared with its ballistic counterpart because of its greater complexity and less favourable (friction/total drag) ratio. Despite the fact that it has no need of low wing-loading, it is heavier in weight than the radiating winged vehicle.

6. Choice of Configuration

These conclusions are quite compatible with the pattern emerging from long-range rocket developments. Here the *absorbing* vehicles are in principle better off because the heat absorbed is less, though this advantage is lost to the *winged* vehicle by its need to use high (L/D) and so high friction drag. On the other hand, the *radiating* vehicles are worse off, as they have to withstand unduly high rates of heat input, though the radiating winged vehicle offers as compensation the reduced load of rocket propellants necessary to cover the required range.

Whether this is adequate compensation or not is difficult to say, but whatever the answer, no doubt the problems of *flying* an aircraft in the hypersonic range involve difficulties not lightly to be undertaken. In mind here for instance is the fact that all aircraft at high speeds lack effective aerodynamic damping, though it is not difficult to arrange that they have adequate aerodynamic stiffness. The control stick, in fact, becomes an acceleration rather than a velocity control, very much as on a helicopter. Again the difficulties of flight at more modest speeds of some of the slender shapes of wings envisaged for hypersonic flight need no emphasis.

In relation to space vehicle re-entry the problem of choice of configuration resolves itself purely on the basis of the off-design condition of re-entry caused by premature failure of the launch rockets or too low an orbital perigee. The heat-absorbing ballistic vehicle scores heavily as its ability to absorb heat is rarely put in question by the form of descent. The radiating vehicles on the other hand are both sensitive to the angle of descent, and if this is unduly large the heating rate is increased: to some extent this is remedied for a winged missile by its ability to pull out of the dive, but premature re-entry due to launch rocket failure, or too large an orbital retardation, both produce more severe heating than is covered in the design conditions. Of course if a man is carried, the higher retardation of the ballistic vehicle, which is certainly dependent on the mode of re-entry, rules it out of consideration for any but the design condition (unless a variable drag device is used), and one is left with the winged vehicle as the only realistic form. Even for such a craft, measures are needed to decrease the likelihood of the high pull-out g, and high heating rates, necessitated by rocket failure. The ascent trajectory needs to be flattened out, much as it was suggested it should be for the winged long-range rocket, and of course for the same reasons.

Premature failure of the launching rockets present similar problems for the long-range missile, and their solutions are similar. No one has yet suggested placing a man inside them, but if they did of course it is only the winged vehicle which involves retardations the human frame could stand, on or off design conditions. But of course they are currently envisaged for roles in which recovery in the event of some failure is of relatively small concern.

7. Re-entry from Parabolic Orbits

Looking in the other direction ahead to re-entry from near parabolic orbits, it is easily established that the problems of heat transfer involved are very acute. An absorbing shell is faced with the problem of a two-fold increase in heat input, at the very least. The winged vehicle suffers rates of heat transfer at least five times those in the descent from a close orbit, unless it makes a large number of passes ("braking ellipses"). A razor edged accuracy is needed to arrange for atmospheric contact at just the right altitude, for even a small error in height can have catastrophic effects.

The absorbing shell offers one solution to this problem of accuracy, if the vehicle is un-manned. To ensure that the orbit perigee is neither so high that another orbit will be described before re-entry, nor so low that the retardation becomes excessive, means for a ballistic missile entering at escape speeds that the perigee must lie in a height band of seven miles if the limit is 10*g*, or 20 miles if the limit is 20*g* (Fig. 9). Entry above this air corridor, and the consequent description of a number of braking ellipses is an acceptable hazard, provided at least the eccentricity of the first is not so large as to try one's patience, and perhaps this allows the corridor to be opened up a little at its top. The high *g* experienced in entries from the bottom of this corridor do not necessarily involve increased heat input, rather the reverse: so perhaps it could be opened up in this direction as well if higher *g* is tolerable.

With a manned vehicle, on the one hand the top of the corridor is to be avoided, not only on the basis of home-sickness and the time factor, but because space is a dangerous place, at least near planets with radiation belts. The bottom of the corridor is equally to be eschewed because of its dangerous accelerations. The corridor is in fact a lot less elastic, and it would certainly pay to use winged lift, as this permits a wider corridor to be used. With a 10*g* limit on pull-out acceleration the height band is 50 miles thick at escape speed, progressively reducing at higher speeds. Roughly it is also proportional to the *g*-limitation: but (L/D) ratio has little effect at least above values of one. Provided it enters this band, lift can always be directed one way or another to allow subsequently the drag to retard the speed in virtually level flight.

However, despite its wider if hard-walled corridor, the winged vehicle depending on radiation cooling will suffer very acutely from the high heating rates associated with a pull-out (if one is needed). And at a distance of ten earth-radii a 50 mile corridor requires either correct alignment of the orbit within about 2 ft. of arc, and no velocity error, or an accuracy of 0·3 per cent in speed with correct direction. Combined errors mean much tighter limitations on accuracy. Whether or not these can be attained with the help of mid-course guidance and rocket control, there is no doubt that there would need to be ample provision of fuel for final corrections close to perigee, though this is certainly not the most efficient time for its use. It would best take the form of a radial thrust to augment the action of lift, at a time when the errors are easiest to discern. Ideally of course it would need less impulse to correct the speed at apogee, were this not so distant that errors would not then be perceptible.

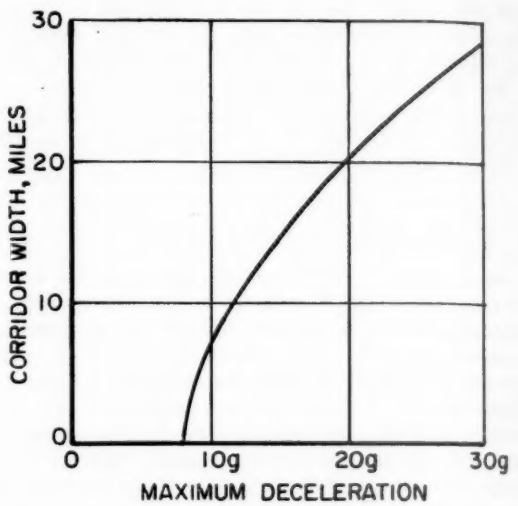

FIGURE 9. Re-entry from parabolic orbit of a ballistic missile.

TECHNICAL NOTES

The Rolling Moments due to Sideslip on High Tailplanes at Subsonic and Transonic Speeds

by

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SOME MEASUREMENTS in the R.A.E. Bedford 3 ft. wind tunnel on a typical high tailplane illustrate a Mach number effect on the tailplane rolling moments due to sideslip which has been apparently overlooked previously. Fig. 1(*a*) shows that the increase in tailplane rolling moment due to sideslip $\frac{\partial C_{lT}}{\partial \beta}$ is much larger than the increase in the fin lift curve slope a_{1F}, Fig. 1(*b*). This extra increase in rolling moment is associated with the increase in the tailplane lift curve slope a_{1T}, Fig. 1(*c*). In fact the rolling moment on this high tailplane varies roughly as the product of the fin and tailplane lifts, as Fig. 1(*d*) shows. A qualitative explanation follows.

Consider the idealised high tailplane shown in Fig. 2. At zero geometric incidence and positive sideslip the fin lift will induce positive and negative incidence distributions on the starboard and port sides of the tailplane. These incidence distributions may be related to equivalent mean incidences

$$\left.\begin{aligned}\alpha_1 &= k_1\beta \\ \alpha_2 &= -k_2\beta\end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (1)$$

where k_1 and k_2 are some functions of a_{1F}. (For slender fins $k_1 = k_2$ and for this model the measurements showed $k_1 \simeq k_2 = k$.) The tailplane rolling moment is then*

$$L_T = \tfrac{1}{2} S_T q\, a_{1T}\, 2k\beta\, lb_T \quad . \quad . \quad (2)$$

where l represents the spanwise centre of the lift distribution due to sideslip.

Hence
$$\frac{\partial C_{lT}}{\partial \beta} = \frac{1}{qS_T b_T}\frac{\partial L_T}{\partial \beta} = a_{1T} kl. \quad . \quad . \quad (3)$$

Now k is a function of the fin lift and the simplest acceptable relationship is

$$k = ma_{1F} \quad . \quad . \quad . \quad . \quad (4)$$

where m is a constant. On this assumption then

$$\frac{\partial C_{lT}}{\partial \beta} \Big/ (a_{1F}\, a_{1T}) = ml = \text{constant} \quad . \quad . \quad (5)$$

Despite the crudeness of the above analysis, it may be seen that equation (5) applies quite well to the experimental results plotted in Fig. 1. The variation of

$$\frac{\partial C_{lT}}{\partial \beta} \Big/ (a_{1F}\, a_{1T})$$

with Mach number is seen from Fig. 1(*d*) to be reasonably small; certainly the large variation apparent in the curve of Fig. 1(*a*) has been considerably reduced. The residual variations may be caused by the small separations which were noticed during oil flow runs.

In tests on another high tailplane the separations were more extensive and reduced $\frac{\partial C_{lT}}{\partial \beta}$ below the value given by equation (5). If the separations are smaller full scale $\frac{\partial C_{lT}}{\partial \beta}$ may be higher than measured in model tests.

If equation (5) is valid for other high tailplanes $\frac{\partial C_{lT}}{\partial \beta}$ can be estimated by extrapolation of the low speed values of $\frac{\partial C_{lT}}{\partial \beta}$, a_{1T} and a_{1F}. The low speed value of a_{1F} can be used to determine the effective aspect ratio of the fin and the variation of a_{1F} and a_{1T} can then be estimated using the graphs of Ref. 1. The tailplane rolling moment (in the absence of separations) at a Mach number M is then

$$\left(\frac{\partial C_{lT}}{\partial \beta}\right)_M = \left(\frac{\partial C_{lT}}{\partial \beta}\right)_0 \frac{(a_{1T}\, a_{1F})_M}{(a_{1T}\, a_{1F})_0} \quad . \quad . \quad (6)$$

Equation (5) is now shown to be compatible with theoretical calculations made for high aspect ratio configurations which give a large Mach number effect on both the fin and the tailplane.

Reference 2 gives the calculated rolling moments for a systematic series of unswept and 45° swept fin tailplane combinations. The fin and tailplane root chords were equal so that for a given fin aspect ratio the tailplane aspect ratio varies as the tail span. The quarter chord lines of the fin and tailplane intersected. These results may be used to find the Mach number effects on the unswept configuration with $A_F = 3{\cdot}0$. The Göthert transformation can be used to transform a configuration of

TABLE I

Fin aspect ratio	*Aspect ratios of affinely related fins*	$\beta = (1-M^2)^{\frac{1}{2}}$	*Equivalent Mach number M*
3·0	3·0	1	0
	2·0	2/3	0·74
	1·0	1/3	0·94

*Since the fin provides an endplate on one side of the tailplane it is probably better to use a_{1T} for the complete tailplane, rather than that for the isolated half tailplane. The former can be measured directly on the model.

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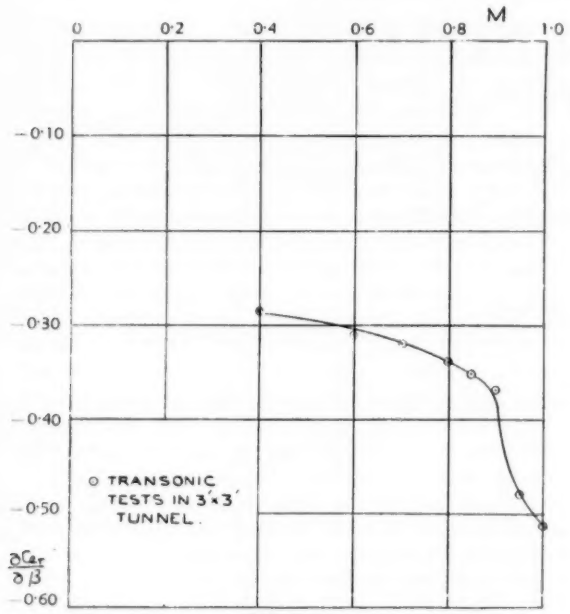
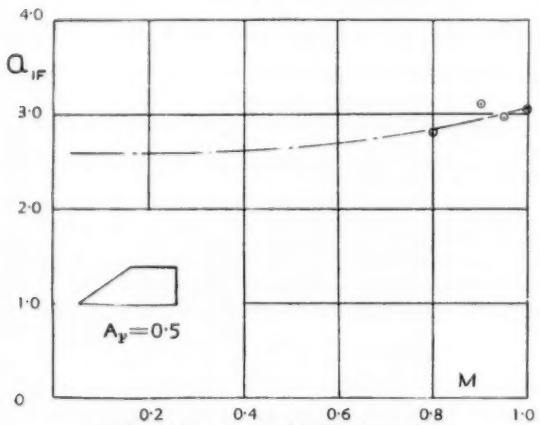
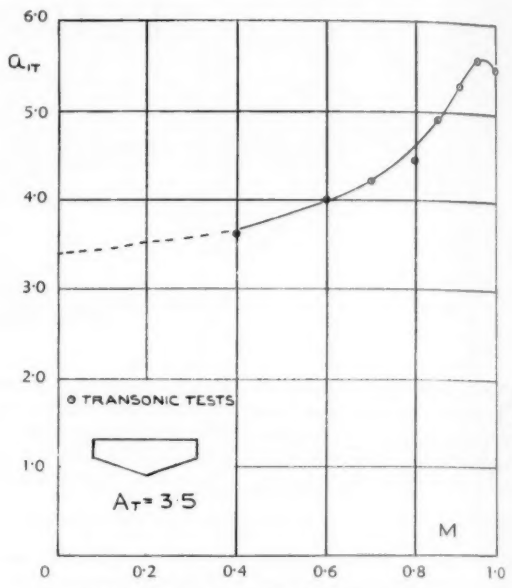


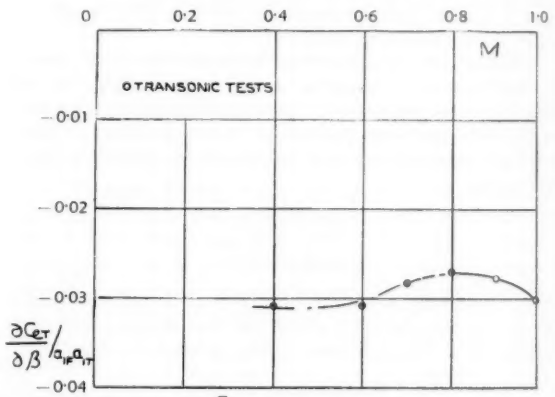
(*a*) Variation of $\frac{\partial C_{lT}}{\partial \beta}$ with Mach number.



(*b*) Variation of a_{1F} with Mach number.



(*c*) Variation of a_{1T} with Mach number.



(*d*) Variation of $\frac{C_{lT}}{\partial \beta} \Big/ a_{1F} a_{1T}$ with Mach number.

FIGURE 1. Measured tail coefficients.

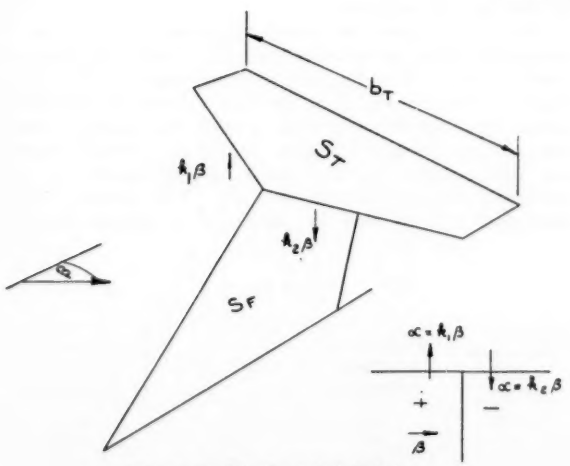


FIGURE 2. Idealised high tailplane.

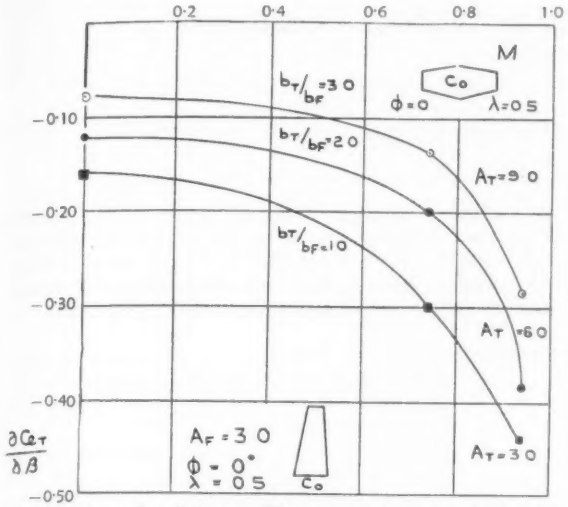
aspect ratio A at a subsonic compressible Mach number M into affinely related configurations of aspect ratio

$$A^1 = A\,(1-M^2)^{\frac{1}{2}}$$

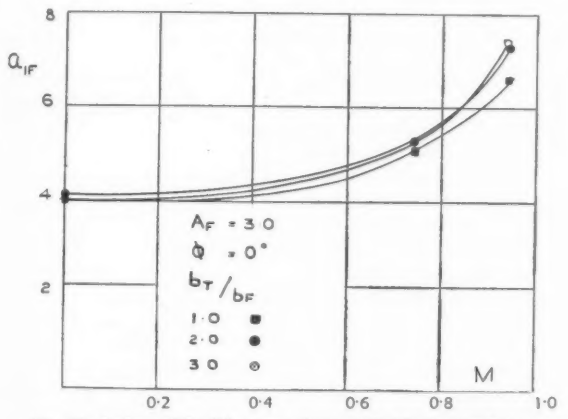
in an incompressible flow. The relations used are given in Table I.

Figure 3 gives $\frac{\partial C_{lT}}{\partial \beta}$, a_{1F} and a_{1T} calculated from Refs. 1 and 2. It is seen that $\frac{\partial C_{lT}}{\partial \beta} \Big/ (a_{1F}\, a_{1T})$ is roughly independent of Mach number. This is an interesting result as it confirms that equation (5) is valid when there is a large Mach number effect on both the fin and the tailplane.

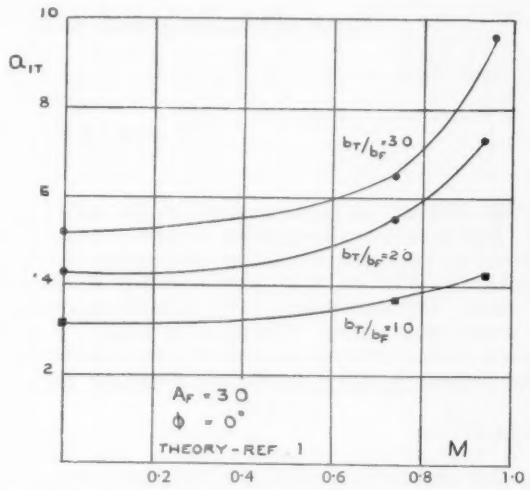
It should be remarked that the theory of Ref. 3 quotes rolling moments on fin tailplane combinations, in addition to the fin lifts. As the author stated (Ref. 3, equation (59)), the boundary conditions satisfied on the tailplane



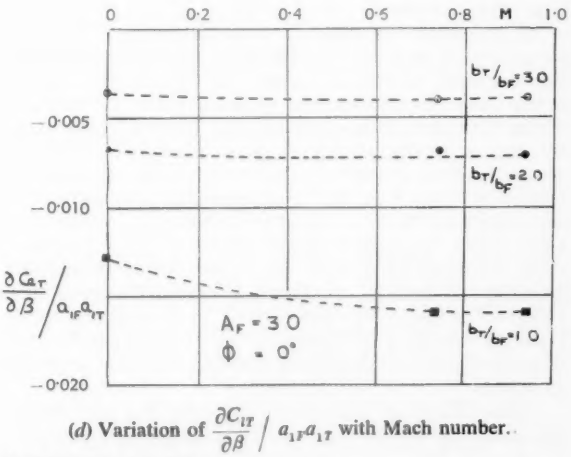
(*a*) Variation of tailplane rolling moment curve slope with Mach number.



(*b*) Variation of fin lift curve slope with Mach number.



(*c*) Variation of tailplane lift curve slope with Mach number.



(*d*) Variation of $\dfrac{\partial C_{1T}}{\partial \beta} \Big/ a_{1F}a_{1T}$ with Mach number.

FIGURE 3. Calculated coefficients for $\phi=0°$, $A_F=3{\cdot}0$.

are such that each side of the tailplane must be considered as twisting differentially as the sideslip increases, while of course the real tailplane will not twist; this may not seriously affect the fin lift, but it obviously affects the tailplane rolling moments. The Mach number effect on the rolling moment given by this theory is

$$\frac{\partial C_{1T}}{\partial \beta} \Big/ a_{1F}=\text{constant},$$

the Mach number effect on the tailplane having been omitted.

Although the emphasis is on high tailplanes, equation (5) applies to a tailplane located in any position on the fin. The recent flight results of Ref. 4 show that the large increase in $\dfrac{\partial C_{1T}}{\partial \beta}$ from $M=0{\cdot}49$ to $0{\cdot}82$ appears to be proportional to the increase in a_{1T}; the estimated increase in a_{1F} is small and its effect is probably within the accuracy of the results.

Equation (5) is recommended because of the fair agreement shown with experiments and calculations.

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Face Wrinkling and Core Strength in Sandwich Construction

by

S. YUSUFF, M.Sc., Dr.Ae.E., A.F.R.Ae.S., A.F.I.A.S.

THE EFFECT of initial waviness on the wrinkling of faces in sandwich construction is studied. Formulae are derived to determine the failing stress when the faces wrinkle due to failure of the core in tension, compression or shear. The importance of core strength requirements in maintaining surface smoothness is noted. A comparison of theory with experiments is made, and the agreement between the two is found to be reasonably good.

INTRODUCTION

A sandwich construction consists of two thin face layers of high-strength material and a thick core layer of lightweight material. The function of the core is twofold. Firstly, it increases the bending rigidity of the faces and second, it stabilises them so that they will not wrinkle until high stress is reached.

If sandwich structure is assumed to be free from irregularity, it can be seen that up to wrinkling instability the core need only have stiffness but not strength, for up to that point the amplitude of wrinkling wave is zero which makes normal stress in core also zero. Hence, in formulae for the wrinkling stress[1-4], only moduli of materials appear, and the strength of the core either in compression, tension or shear is absent. In sandwiches with aluminium alloy faces and cores, such as end-grain balsa, which have high values of moduli, wrinkling stress, computed from these formulae even with reasonable value of reduced modulus of facings, appear[5] to be well above that observed in test. This discrepancy may be due to other types of wrinkling in which the core strength and initial irregularity may be thought to influence the face wrinkling as follows.

Since sheets of facings are not truly flat and neither the thickness of the core nor of bonding is uniform, it is apparent that initial irregularity or waviness is present in sandwich construction. Any waviness in the direction of loading will be amplified with the result that tensile forces are set up in the core. On increasing the load this amplification becomes greater and greater and finally the failure of the sandwich may occur earlier than expected, when the force in the core exceeds its ultimate tensile strength. Similar reasoning will lead to wrinkling due to failure of the core in compression or in shear. Hence, it is desirable not only to know the reduction in the wrinkling stress due to initial waviness, but it is also necessary to determine the core strength requirements to achieve the design stress for a given minimum value of initial waviness. This problem is the subject matter of the present note in which the results of theory of wrinkling given by the author in Ref. 4 form the basis.

It should be noted that similar reasoning has been used by Wan[5] and Williams[3] in face wrinkling phenomenon. Wan, making use of Donnell's assumption for probable initial deviations of the face, has calculated the load at which the core would break. His theoretical result indicated that the critical stress in wrinkling stability depends not only on the value of Young's modulus, but also on the strength of the core. Williams has related the strength of the core in tension and shear to an arbitrarily assumed initial irregularity which, to ensure laminar flow in a wing, is assumed to have a maximum admissible value (initial wave amplitude/critical wavelength=0·0005 to 0·001).

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NOTATION

A_0	amplitude of initial waviness
A	amplitude of additional deflection
b	thickness of core
E_c	Young's modulus of core in direction perpendicular to faces
E_f	Young's modulus for faces
G_c	shear modulus of core in plane xy
I	moment of inertia of face of unit width ($=t^3/12$)
K	modulus of foundation or spring constant
l	one-half wavelength
P	load in face of unit width
t	thickness of face
T_c	ultimate tensile or compressive strength of core
W	width of marginal zone
x, y	Cartesian co-ordinates
σ	compressive stress in face
σ_{cr}	wrinkling stress
σ_f	failing stress
τ_c	ultimate shear strength of core
ω_0	initial waviness
ω	additional deflection

FACE LAYER AS A BEAM ON AN ELASTIC FOUNDATION

The wrinkling phenomenon of a sandwich face layer is generally investigated by considering it as a beam supported by an elastic foundation. The author in Ref. 4 has considered two cases of symmetric type of face buckling depending on whether the thickness of the core can be regarded as finite or infinite. Since the results of this reference form the basis of the present note, they are briefly summarised in the following.

The modulus of foundation corresponding to a core, which can be homogeneous (isotropic) or grained (aelotropic), is determined for the two symmetric cases, and the buckling phenomenon of a face as an elastically supported beam is investigated. Since the wavelength of wrinkling is very small, the beam is regarded as if it were infinitely long.

In the case in which the core is sufficiently thick to be treated as infinite, because a short wave on the surface can hardly have any effect upon the material in the middle of the core, an assumption is made that displacements in the core are restricted to a marginal zone of width W. The displacements are assumed to be given by

$$\omega = A \frac{y}{W} \sin \frac{\pi x}{l} \quad . \quad . \quad . \quad (1)$$

in which the zone of displacement W adjacent to a face is shown to be

$$W = 0{\cdot}72l \sqrt[3]{\left(\frac{E_f E_c}{G_c^2}\right)} \quad . \quad . \quad . \quad (2)$$

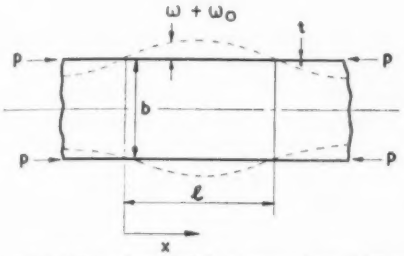

FIGURE 1. Wrinkling of sandwich construction; thickness of the core is small.

The formulae, for the wrinkling stress corresponding to the two cases considered, are:

(*i*) when

$$b < 2W$$

$$\sigma_{cr} = \sqrt{\left(\frac{2}{3} E_f E_c \frac{t}{b}\right)} \quad . \quad . \quad . \quad (3)$$

and

(*ii*) when

$$b > 2W$$

$$\sigma_{cr} = 0{\cdot}96 \sqrt[3]{(E_f E_c G_c)} \quad . \quad . \quad . \quad (4)$$

In the inelastic region, these two equations can be respectively modified to

$$\frac{\sigma_{cr}}{\eta^{1/2}} = \sqrt{\left(\frac{2}{3} E_t E_c \frac{t}{b}\right)} \quad . \quad . \quad (5)$$

and

$$\frac{\sigma_{cr}}{\eta^{1/3}} = 0{\cdot}96 \sqrt[3]{(E_t E_c G_c)} \quad . \quad . \quad (6)$$

where η is the plasticity correction factor for facing material and is defined as $\eta = E_r/E_t$; the reduced modulus E_r can be obtained from the formula

$$E_r = \frac{2E_t E_t}{E_t + E_t} \quad . \quad . \quad . \quad (7)$$

where E_t is the tangent modulus.

The derivation of these formulae for the wrinkling stress is based on the assumption that the sandwich structure is free from initial irregularities. In many cases these results appear to be adequate. However, it is desirable to consider the types of wrinkling in which the core fails in tension, compression, or shear as a consequence of initial imperfections. This is done in the following sections.

THE EFFECT OF INITIAL WAVINESS ON DEFLECTIONS

Any initial waviness present in a sandwich face can be represented by a Fourier series, but for the sake of simplicity let it be assumed that, in both cases of symmetric wrinkling (Figs. 1 and 2), it is given by

$$\omega_0 = A_0 \sin \frac{\pi x}{l} \quad . \quad . \quad . \quad (8)$$

If each of the faces is now subjected to an axial compressive force P, additional deflection ω will be produced so that final ordinates of the deflection curve of a face are $(\omega + \omega_0)$. Then the differential equation of the buckling of the face of unit width, elastically supported, is given by[4]

$$\frac{d^4\omega}{dx^4} + \frac{P}{EI}\frac{d^2\omega}{dx^2} + \frac{K\omega}{EI} = -P\frac{d^2\omega_0}{dx^2} \quad . \quad (9)$$

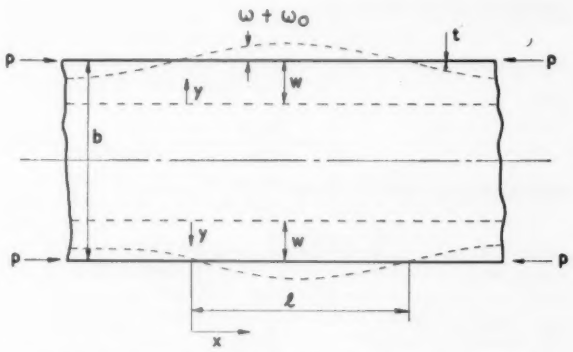

FIGURE 2. Wrinkling of sandwich construction; thickness of the core is large.

It can be shown that the solution of this equation is

$$\omega = \frac{A_0}{(P_m/P) - 1} \sin \frac{\pi x}{l} \quad . \quad . \quad (10)$$

where

$$P_m = \frac{4\pi^2 EI}{l^2} + \frac{Kl^2}{4\pi^2} \quad . \quad . \quad . \quad (11)$$

The amplitude of the additional deflection

$$A = \frac{A_0}{(P_m/P) - 1} \quad . \quad . \quad . \quad (12)$$

is obtained by magnifying the amplitude of the initial waviness in the ratio $1/(P_m/P) - 1$. Because at the critical wavelength P_m is minimum for any given loading P, this ratio has its largest value and therefore the stresses produced in the core are maximum. Hence the most dangerous initial wavelength is the critical wavelength of wrinkling of faces. For this reason we need consider only those initial irregularities which have the same wavelength as the critical wavelength of wrinkling. Under this condition equation (12) can be written as

$$A = \frac{A_0}{(\sigma_{cr}/\sigma) - 1} \quad . \quad . \quad . \quad (13)$$

TENSION OR COMPRESSION FAILURE OF THE CORE

From equation (13), it can be seen that, as compressive stress increases, the amplitude of additional deflection rapidly increases; a situation will soon arise when the ultimate tensile (or compressive) strength of the core is exceeded. Then the failure of the sandwich takes place owing to the failure of the core (strength of bond is assumed to be greater than that of the core). The failing stress, σ_f, for the two cases of wrinkling type considered here, can be determined as follows:

(*i*) For

$$b < 2W,$$

taking the maximum amplitude of the additional deflection at failure as

$$A = \frac{T_c b}{2E_c} \quad . \quad . \quad . \quad . \quad (14)$$

equation (13) is written as

$$\frac{T_c b}{2E_c} = \frac{A_0}{(\sigma_{cr}/\sigma_t)-1} \quad . \quad . \quad . \quad (15)$$

or

$$\frac{\sigma_{cr}}{\sigma_t} = \frac{2A_0E_c}{T_c b} + 1 \quad . \quad . \quad (16)$$

combining equations (16) and (5), we have

$$\frac{\sqrt{\left(\frac{2}{3}\eta E_t E_c \frac{t}{b}\right)}}{\sigma_t} = \frac{2A_0E_c}{T_c b} + 1 \quad . \quad . \quad (17)$$

(*ii*) For

$$b > 2W,$$

the maximum tensile or compressive strain in the core, by using equation (1), is

$$\varepsilon_{max} = \left(\frac{\partial \omega}{\partial y}\right)_{max} = \frac{A}{W} \quad . \quad . \quad . \quad (18)$$

Taking $T_c = E_c \varepsilon_{max}$, we obtain, from equation (18), the following value for the amplitude of additional deflection

$$A = \frac{WT_c}{E_c} \quad . \quad . \quad . \quad . \quad (19)$$

which on making use of equation (2) becomes

$$A = 0{\cdot}72\, tT_c \sqrt[3]{\{E_t/(E_cG_c)^2\}} \quad . \quad . \quad (20)$$

Substituting equations (20) and (6) in (13), we have

$$\frac{0{\cdot}96\sqrt[3]{(E_tE_cG_c)}}{\sigma_t} = 1 + 1{\cdot}39\,\frac{A_0}{tT_c}\sqrt[3]{\{(E_cG_c)^2/E_t\}} \quad . \quad (21)$$

In the inelastic region, this equation is modified to

$$\frac{0{\cdot}96\sqrt[3]{(\eta E_tE_cG_c)}}{\sigma_t} = 1 + 1{\cdot}39\,\frac{A_0}{tT_c}\sqrt[3]{\{(E_cG_c)^2/(\eta E_t)\}} \quad . \quad (22)$$

By means of equations (17) and (22), for any given initial waviness and core strength, the failing stress can be determined, or conversely, for any given initial waviness, the core strength required to achieve a particular stress can be computed.

SHEAR FAILURE OF THE CORE

Shear deformations in the core, as stated before, are considered when it is sufficiently thick ($b > 2W$). In this case, using equation (1), we have the maximum shear strain

$$\gamma_{max} = \left(\frac{\partial \omega}{\partial x}\right)_{max} = \frac{A\pi}{l_{cr}} \quad . \quad . \quad . \quad (23)$$

Taking the ultimate shear strength as

$$\tau_0 = G_c\gamma_{max} \quad . \quad . \quad . \quad (24)$$

we obtain, from equations (23) and (24), the amplitude of additional deflection

$$A = \frac{\tau_c l_{cr}}{\pi G_c} \quad . \quad . \quad . \quad . \quad (25)$$

combining equations (25) and (13), we have

$$\frac{\sigma_{cr}}{\sigma_t} = 1 + \frac{\pi A_0 G_c}{\tau_c l_{cr}} \quad . \quad . \quad . \quad (26)$$

TABLE I

COLUMN TEST DATA FOR SANDWICH PANELS[7]. PLASTIC HONEYCOMB CORE

$E_c = 23{,}000$ lb./in.² Crushing Strength = 270 lb./in.²
$G_c = 8{,}200$ lb./in.² $2W/t = 21{\cdot}8$

Thickness and material of facing	*Overall thickness* (in.)	*Column length* (in.)	*b/t*	*Failing stress*	
				Test (lb./in.²)	*Theory* (lb./in.²)
0·032 in. 24S-T	1·016	17·86	29·7	40,300	41,000
	1·018	9·91	29·7	42,100	
	1·007	5·99	29·2	46,300	
0·0315 in. 75S-T	0·970	29·9	28·8	51,800	54,000
	0·969	19·9	28·8	53,400	
	0·971	9·6	28·8	56,800	
	0·972	6·1	28·8	59,500	

Substituting in this equation the values of the critical stress from equation (6) and critical wavelength ($l_{cr} = 1{\cdot}307t\sqrt[6]{\{E_t^2/(E_cG_c)\}}$ from Ref. 4), we have

$$\frac{0{\cdot}96\sqrt[3]{(\eta E_tE_cG_c)}}{\sigma_t} = 1 + \frac{0{\cdot}765\pi G_cA_0}{\tau_c t\sqrt[6]{\{(\eta E_t)^2/(E_cG_c)\}}} \quad (27)$$

As in the case of tensile or compressive failure of the core, the determination of the failing stress due to shear failure of the core depends on the initial waviness and the shear strength of the core.

Note that in all cases of core failures considered it is assumed that stress-strain curves for the core is linear up to its maximum strength. However, for cores whose stress-strain curve cannot be approximated in this way an appropriate correction such as the replacement of Young's modulus by Secant modulus can be considered.

COMPARISON OF THEORY AND EXPERIMENTS

A comparison of the theory is made with test data, selected from Refs. 5, 7 and 9, covering 24S-T and 75S-T aluminium alloy face materials with honeycomb, end-grain

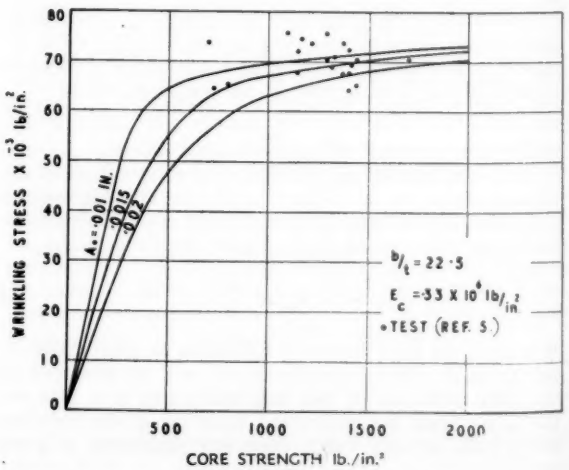

FIGURE 3. Comparison of typical test results for sandwiches of end grain balsa core and 75S-T facings with analysis.

TABLE II

COMPRESSIVE STRENGTH OF SANDWICH SPECIMENS WITH 24S-T. ALCLAD ALUMINIUM ALLOY SHEET FACINGS[9]. CELLULAR CELLULOSE ACETATE CORE

$E_c = 40{,}700$ lb./in.^{2} $T_0 = 201$ lb./in.^{2}

$G_c = 3{,}500$ lb./in.^{2} $2W/t = 46{\cdot}4$

Thickness of faces	*Overall thickness*	b/t	*Failing stress*	
			Theory	*Test* (lb./in.^{2})
(in.)	(in.)		(lb./in.^{2})	
0·0125	1·019	79·5	42,000	42,100
0·0185	1·030	53·7	45,000	48,600
0·032	1·043	30·6	41,000	38,300

balsa, and cellular cellulose acetate core materials. Reduced modulus for 24S-T faces is obtained from Ref. 8 and the tangent modulus of 75S-T faces is obtained from Ref. 6.

A part of the test result, from Ref. 5, on column strength of sandwich panels is given in Table I. Assuming the panels to be free from initial irregularities, the critical stresses of these panels are computed from equation (6), and they are given in the last column of Table I.

In order to compare theory and experiment, Wan[7] has published some experimental results on sandwich panels having end-grain balsa core with 75S-T faces. The same result has been utilised for comparison with the present theory. For $A_0 = 0{\cdot}001$ in., $0{\cdot}015$ in. and $0{\cdot}002$ in., $G_c = 20{,}000$ lb./in.^{2}, $b = 0{\cdot}5$ in., and for various values of core strength, the failing stresses have been calculated from equation (17). The result is shown in Fig. 3.

Finally, from Ref. 9, three examples of sandwich plate having cellular cellulose acetate core are chosen. Assuming $A_0 = 0{\cdot}001$ in. the failing stresses have been computed from equation (22) or (17) according as b is greater or less than $2W$. The result is given in Table II.

It can be seen that the agreement between theory and experiment is reasonably good.

ACKNOWLEDGMENT

Acknowledgment is made by the author to Bristol Aircraft Limited for permission to publish this note.

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Graduates' and Students' Section

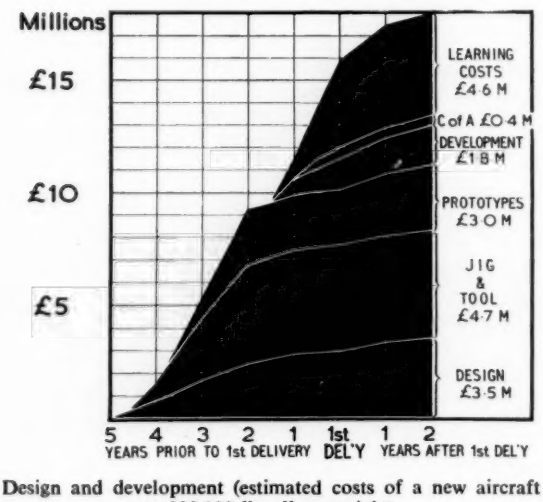
President's Lecture

Problems and prospects of British aviation were surveyed by Mr. Peter G. Masefield, this year's President of the Society and the Managing Director of Bristol Aircraft Ltd., in a lecture before the Section on 27th January. Particularly interesting were the figures he quoted in discussing the post-war performance of the industry and comparing its costs with those of the U.S.

Since 1945 Britain has produced about 27,500 aircraft of 115 different types, at a cost of £3,500 million; 85 per cent of this has been spent on military production. More Meteors had been built than aircraft of any other type and their production run totalled more than 3,000 aircraft; in order thereafter have come the Vampire, Hunter, Venom and Canberra.

The increasing cost and complexity of aircraft is shown by a comparison of the output for 1946 and 1958. In 1946 some 2,700 aircraft were produced at a total cost of £90 million, whereas in 1958 only 800 aircraft were built, but their total value was £400 million. Structure-weight cost rose from some £2 per lb. to £12·5 per lb.

In discussing exports, Mr. Masefield said that despite the much lower labour costs in Britain the prices of British and U.S. air liners were similar. If the Vickers VC 10 were included, the mean empty weight of current British air liners was 86,000 lb. and their cost per lb. of empty weight was £14. Comparable figures for U.S. air liners were 90,000 lb. and £13 7s. The leading U.S. companies which built air liners received substantial military support; military production by Douglas and Boeing last year accounted for 79 per cent and 75 per cent of their total outputs respectively.



Design and development (estimated costs of a new aircraft of 200,000 lb. all-up weight).

About 234,700 people were employed in the British Aircraft Industry last year; this figure will fall before stability is reached. Mr. Masefield said that there was a shortage of technical staff; the difficulty in future would not lie on the technical side, but in providing sufficient production work for the skilled craftsman.

In discussing the future Mr. Masefield pointed out the large potential market provided by what is known in the U.S. as " general aviation." Aircraft for this field of executive and business flying have been on the whole neglected by British manufacturers.

Another future project of importance was the supersonic transport; here Mr. Masefield favoured a speed at a Mach number of 3 or a little higher. If Britain designed a Mach 2·2 transport, it might well be superseded before it entered service if the U.S. produced a faster air liner. But above $M=2{\cdot}2$ steel structures would have to be used and this involved greater technical risks.

An interesting point during the discussion covered hovercraft operating costs. Mr. Masefield believed that at the present stage of hovercraft development their ton-mile operating costs were about the same as the operating costs of aircraft such as the Bristol Freighter and DC-3, although later developments might improve their economy.

Future lectures and visits

Mr. Thurstan James, the Editor of *The Aeroplane and Astronautics* will speak to the Section on Wednesday 6th April on his experiences of thirty years in aeronautical journalism.

On Saturday 21st May a visit has been arranged to Vickers-Armstrongs (Aircraft) Ltd., at Weybridge, Surrey for 9.30 a.m. We will see Viscount and Vanguard production, and may catch a glimpse of jigs for the mighty VC 10.

Applications for the visit should be made to the Hon. Visits Secretary: N. R. Craddock, 5 Oxleay Road, Harrow, Middlesex.

THE BRANCHES

In the two previous issues of this page, we have outlined the growth, movement and the activities of the Branches Conference and Committee. Before passing to individual Branches and current news, it may be appropriate to quote the actual Branches Charter.

Branches Charter

Under the Charter of Incorporation of the Royal Aeronautical Society granted by letters patent of His Majesty the King of the 17th January 1949 and as amended on 3rd February 1950, the Royal Aeronautical Society is constituted for the general advancement of aeronautical art, science and engineering and more particularly for promoting that species of knowledge which distinguishes the profession of aeronautics and for those purposes inter alia it has the power to establish sections and branches of the Society in the British Commonwealth.

The Council of the Royal Aeronautical Society under the previous rules of the Society confirmed in the Charter of Incorporation, did on ..... approve the formation of the ..... branch of the Royal Aeronautical Society. The object of this branch shall be the formation of a nucleus of informed technical opinion on technical matters and the furtherance of the objects of the Royal Aeronautical Society. Membership of the branch shall be open to all persons without restriction.

President.....

WHILE the first Branches of the Society were formed in 1918, the earliest extant one is COVENTRY which immediately followed on the amended Constitution of February 1926 and was the first Branch to be so formed. This was in the same month and Coventry was most successful from its inception, although in common with all the Branches, it suffered a reduction of membership in the early 1930s.

By 1938, however, the numbers had again risen and in 1939 reached the handsome figure of 380. Despite the difficulty of getting Lecturers at the beginning of the War, the Branch was only inactive for a short time and by January 1940 a new series of Lectures had been started. But by 1942 it again became necessary to close down until March 1945.

1945/46 was the 21st Anniversary; Membership was then at the record total of 573 Members, of whom 80 were Members of the main Society. Owing to the unsettled transition stage following the war, when many moved away from Coventry or away from the Industry, the following two years showed a decline and at March 1948, the figure stood at 304.

Today it is 404, with the high proportion of 243 Main Society Members. If we have tended to place emphasis on numbers, it has been to show the larger part now being played by Society Members in the Branches, which reflects the increased status of the Society itself over these years.

The interests of Coventry are as varied as its "member" Firms, in the main being Armstrong-Whitworth Aircraft, Bristol-Siddeley and Alvis Engines, Dunlop, B.T.H. and Lockheed. With such a cross-section of the Industry, the lectures are very varied, as have been the many venues in the City.

The Coventry Committee was once two, the "General" keeping in touch with the many Firms, and the "Executive" dealing with the Branch as an entity. With an amalgamation of the two came about one of the largest Committees in the Society—but, so they report, "it seems to work."

Officials of the Committee have changed infrequently and in these many years there have only been two Presidents—Mr. J. D. Siddeley (the late Lord Kenilworth), and Mr. H. M. Woodhams, now an "elder statesman" in that he was an Honorary Auditor at the very beginning, 34 years ago. Another of meritorious and long service is Mr. E. D. Keen, who has been Secretary and Chairman and is now Vice-President, a post created in recognition of his work.

Chairmen have been Major F. M. Green, Major Shilson (first Chairman of the Branches Committee), Air Vice-Marshal Sir John Higgins, Mr. E. D. Keen, Mr. W. J. Peters.

As with all Branches, the Summer programme includes visits to other Firms in the Industry. But can any claim, as on a visit to Rolls-Royce, an attendance of about 250? The hosts are recorded as receiving this "very calmly," but some credit should be accorded to the Coventry Hon. Secretary.

Mr. C. H. Sculthorpe is another of long standing and has been Secretary since 1948; bringing the story up to date he reminds all readers that the Coventry Main Society Lecture is on the 7th April, on "The Optimum Size of Rocket Engines" by J. E. P. Dunning. While the subject is now one of everyday acceptance, it is interesting, by contrast, to speculate on the state of the art when Coventry first associated itself with the Society.

It is an especial pleasure to record this brief history of our oldest Branch. Reverting to 1926, we see that Coventry was modern in its thinking, right from its first lecture—the "Autogyro" by Mr. W. H. Farren.

If the Society can celebrate so odd an Anniversary as its 94th, then the JOURNAL has no hesitation—and almost to the month—of congratulating the Coventry Branch on its 34th.

Branch News

LUTON reports that a "Young People's Lecture" was recently held in conjunction with the local education authorities. Some 400 youngsters listened to a fine performance by Bill Bedford on "A Day in the Life of a Test Pilot," with Hawker's film on the Hunter Trainer. Luton have now offered prizes for essays on "Round the World in Eighty Hours" which should furnish the material for yet another lecture—if not a film.

BROUGH, who inaugurated this type of lecture organised their third one in January with Wing Commander J. H. Lewis, A.F.C., who commanded the R.A.F. Antarctic Detachment with Sir Vivian Fuchs. "Flying with the Trans-Antarctic Expedition" was illustrated by colour slides and film, and is said to have spell-bound 600 children for 80 minutes. Such an audience must probably rank as a record for any R.Ae.S. Lecture, but the Chairmen of the two Education Committees of Hull and the East Riding have suggested taking over the City Hall for 1961. This seats 2,000 . . . .

At BRISTOL, two historically-minded Members have brought to light an aero-engine exactly 50 years old, to coincide with the 50th Anniversary (19th February 1960) of the Bristol Aeroplane Company. The engine is a five cylinder Viale of 1910, made in France and bought by A. V. Roe for his 1912 monoplane and biplane. It was next used by Captain Barnwell in the Bristol "Babe" of 1919, and was then virtually forgotten, and certainly lost since 1938.

Through the help of Sir Arnold Hall and Bristol-Siddeley Engines Ltd., the Viale engine has been restored and after exhibition at the Barnwell Memorial Lecture (appropriately given by Sir Roy Fedden) alongside a Jupiter and Hercules, is being presented by the two historians to the Society.—G. W-W.

The 1910 Viale engine. On the left, Mr. Gordon Wansbrough-White and Mr. C. H. Barnes who found it—and right, the five cylinder engine restored to "show condition."

The Ninety-Fourth Anniversary Luncheon 12th January 1960

MORE THAN 400 MEMBERS and guests attended a Luncheon held by the President, Mr. Peter G. Masefield, M.A., F.R.Ae.S., Hon. F.I.A.S., M.Inst.T., and the Council at the Dorchester Hotel, Park Lane, London, W.1 on 12th January, 1960 on the occasion of the Ninety-fourth Anniversary of the founding of the Society and to celebrate the Jubilee of the "Golden Year of British Aviation—1910."

When the Luncheon was first planned the Prime Minister had accepted the President's and Council's invitation to be present but plans for his tour of Africa, at the beginning of January then intervened; fortunately the Minister of Aviation, the Right Hon. Duncan Sandys, M.P., agreed to deputise for the Prime Minister and be the Society's Principal Guest.

The distinguished company included eight of the Society's oldest members, as follows: Brigadier-General Sir H. Osborne Mance, Companion, member since 1899; Lord Brabazon of Tara, Honorary Fellow and Past President, member since 1909; Dr. A. P. Thurston, Fellow, member since 1908; Sir Bennett Melvill Jones, Honorary Fellow, member since 1911; Major A. R. Low, Fellow, member since 1911; and the following Founder Members (defined by the By-Laws as "Every person who on 1st November 1911 was on the Register as a member")—Air Commodore H. Le M. Brock (1911), Captain H. F. Jackson (1911), Air Chief Marshal Sir Arthur Longmore, G.C.B., D.S.O. (1911), H. T. Winter (1911). To the Council's regret, a number of other members of long standing were unable to be present.

"BRITISH AVIATION"

After the toast to Her Majesty The Queen, the toast of "British Aviation" was proposed by the President.

The President, Mr. Peter G. Masefield: When we first decided to hold this Luncheon, the purpose was to celebrate two anniversaries—The founding of the Royal Aeronautical Society—94 years ago today on 12th January 1866 and, the anniversary of what seems—in retrospect—that Golden Year Nineteen Hundred and Ten—which saw the first flowering of so much that has been important in British Aviation ever since.

Today, in fact, I am not sure whether we are celebrating just that—the anniversaries of the past—or the fresh promise of great new things for the future.

Day by day, events crowd in on each other thick and fast in Aviation. Today is no exception. So I think that we are, in fact, today celebrating both past and promise.

May 1960 be, in the end, as great a year for British Aviation as was 1910.

But, whatever it is, my first —and very pleasant—duty is to bid you welcome to this Anniversary Luncheon.

You know, it is said that if an earthquake were, suddenly, to engulf the British Isles, the British people would contrive to meet and dine, somewhere among the rubble, to celebrate the event. Some may feel that today there has been an earthquake which has shaken British Aviation into a new form.

Anyway, these two anniversaries are milestones in British Aviation.

To mark these two past anniversaries, I have the pleasure and privilege of reading out a message from our Patron, Her Majesty The Queen, in reply to a message of loyal greetings sent to her on your behalf.

> "*The Queen sincerely thanks the Council and Members of The Royal Aeronautical Society on the occasion of the celebration of their 94th anniversary and the Golden Jubilee of the year* 1910 *for their kind and loyal message which Her Majesty, as Patron of the Royal Aeronautical Society, greatly appreciates.*"

We are very grateful to Her Majesty.

The Right Hon. Duncan Sandys, M.P., Minister of Aviation being greeted by the President, Mr. Peter G. Masefield.

I have also messages from:

The Institute of the Aeronautical Sciences, New York. The Canadian Aeronautical Institute, A.F.I.T.A. in France and The Aeronautical Society of India.

Now this is an aeronautical "family gathering" at the start of what may well be a momentous year—50 years after British Aviation really got going. And we, of the Society, are delighted to welcome not only some 400 members of the Society itself, but also a number of honoured and distinguished guests—headed by our Guest of Honour:—The Right Honourable Duncan Sandys, our Minister of Aviation.

We are delighted to have with us too, The Right Honourable Edward Heath, the Minister of Labour, and a very old friend of mine, since the days when he and I worked together in Ariel House at the old Ministry of Civil Aviation. The fact that the Minister of Labour is also an Aviation man is not always remembered.

And, if I may single out, from among our many distinguished guests, just one other—Sir Thomas Pike. This is, I believe, just about his first official function as Chief of the Air Staff. Everyone in Aviation wishes him well in his new high office.

These are difficult times. And I may say that—in the present state of play—one of the more difficult things has been the arrangements of the Table Plan for this lunch—although it is not so much what is on the table that matters as what is on the chairs.

In arranging the seating, the problem is that one does not know, from day to day, who is merged with who in aviation—who is married, who are just "living together" and who are separated—in fact who does what and with whom. So if there are any embarrassing "juxta-positions" please blame it on the "1960 pace of events."

Indeed, day by day, we are getting the answer to "The Riddle of the Sands." Its all pretty interesting.

We are, of course, specially pleased to be able to welcome the match maker himself—Mr. Sandys—as our Guest of Honour.

In welcoming Mr. Sandys we, of course, have to say that we are very sorry that the pressure of international business has prevented the Prime Minister, Mr. Harold Macmillan, being with us also today.

As I think you know, Mr. Macmillan had accepted our invitation to be present at this lunch, before he knew of his visit to Africa, and we had felt that the Prime Minister's presence would be a great encouragement to all of us in Aviation. He has, however, sent us a message of regret and good wishes.

Our regret in the absence of the Prime Minister does not, however, make our welcome to Mr. Sandys any less sincere.

Our invitation to the Prime Minister was before the Election and before the appointment of a "Minister of Aviation." As one of our objectives in inviting the Prime Minister was to press for a Minister of Aviation, we can feel that "the wish has been the father of the Sandys."

Minister—we are delighted at your appointment—and to have you with us.

Now these Anniversaries we are celebrating.

Ninety-four years ago, the Royal Aeronautical Society was founded under the title "The Aeronautical Society of Great Britain."

That was 37 years *before* the Wright Brothers made the first powered, controlled, flight—and 43 years before the first powered-flight as a passenger by an Englishman—Griffith Brewer, a Past-President of this Society.

The very first meeting of the Society was, in fact, at Argyll Lodge, Campden Hill, on 12th January, 1866.

The Eighth Duke of Argyll (George Douglas Campbell)—a Fellow of the Royal Society and a Past-President of the British Association—was in the chair.

Incidentally, his son the Ninth Duke of Argyll, became the first President of the Royal Aero Club in 1901.

Now, Laurence Pritchard—our much respected former Secretary over 25 years—has drawn attention to the fact that one of the other claims to fame of the Eighth Duke of Argyll was the fact that he put up a series of posts to mark his property.

These posts were of such a height that they came to be used by his gillies as "back scratching" posts—all the while exclaiming "God Bless the Duke of Argyll."

Like our first President, we of The Society have been concerned since then with many men and many posts—although perhaps of a different sort. But, as Laurence Pritchard remarks, one cannot help feeling that a good many of those posts also have been used for "back-scratching" purposes—the while exclaiming, perhaps,—in up to date fashion—"God Bless the Minister of Aviation."

At least—a lot of people no doubt hope that they may legitimately exclaim such a thing in the future.

At that first meeting of the Society ninety-four years ago, there were five men, as well as the Duke of Argyll, who set up the Society "to foster and develop the Science of Aeronautics."

The Society's oldest surviving member, Brigadier-General Sir H. Osborne Mance, member since 1899.

There were James Glaisher, an astronomer and balloonist; Francis Wenham, a Bristol marine engineer and scientific instrument designer; Hugh Diamond, a doctor of medicine; James Butler, a wine merchant; and Francis Brearey, gentleman of leisure and first Honorary Secretary of the Society. A thoroughly mixed bag—with widely different scientific and engineering interests.

And that is what the Society has been, ever since—an association of those concerned with all aspects of aeronautical activity in the scientific and engineering planes.

The Society has always been in the van of progress, and its Members have taken part in all the great advances in Aviation during the past 50 years.

The second anniversary which we are celebrating today is the Golden Jubilee of, what has been termed, that "Golden Year of British Aviation"—1910—the year in which—after small beginnings in 1909—British Aviation suddenly came into flower.

They say—of course—that "the past always looks better than it was: it is only pleasant because it is not here."

But how pleasant to have with us today some of the choicest blooms of that "blooming" wonderful year—1910.

Lord Brabazon—holder of The Royal Aero Club Aviator's Certificate Number One, which was awarded in March 1910—and a Past-President of this Society.

Sir Thomas Sopwith—holder of Royal Aero Club Aviator's Certificate Number 31. Sir Thomas established a British distance record with a flight of 169 miles from Eastchurch to Belgium in December, 1910.

Up to the last minute we were looking forward to having with us Sir Frederick Handley Page, another of our Past Presidents, who founded his great—and still very independent—Company in 1909. Unfortunately, Sir Frederick is not well and has sent his good wishes and regrets. We wish him a speedy recovery.

We have here too—Sir Osborne Mance, our oldest living Member, who was writing on the prospects of Aviation in Nigeria in the Society's Journal, fifty years ago, in 1910.

I wonder what Sir Osborne would have thought then had he known that our Prime Minister would fly to Nigeria overnight, 50 years later.

We have here also Dr. A. Peter Thurstan, who 50 years ago was not only writing on aerodynamics in the Society's Journal but also experimenting at Crayford on a monstrous flying machines with Sir Hiram Maxim.

Five people who have seen the whole 50 years in aviation.

Certainly, in 1910—50 years ago—Aviation in Britain suddenly blossomed.

Aerodromes—or "flying fields"—shot up at Eastchurch, at Hendon, at Brooklands, at Filton, at Dagenham, on Salisbury Plain and at Beaulieu.

Handley Page, Blackburn, the Short Brothers, A. V. Roe, the Bristol Company, de Havilland at Newbury, Martin and Handysyde and Cody, all built aeroplanes—and what is more, flew them.

In 1910 too, the Aeronautical Society drew up, with the Aero Club—which became "Royal" in that year—and with the Air League, a "Gentleman's Agreement" on the division of territory. It said:

For the purposes of this agreement:—

"The Aeronautical Society shall be regarded as the paramount scientific authority on aeronautical matters, The Aero Club in all matters of sport and The Air League, the paramount body for patriotic movements and for education."

And that stands to this day.

1910 was the year in which, in reply to a body of embryo aircraft constructors—then, as now—seeking Government help, the Secretary of State for War wrote as follows:—

"Much as we would like to help you by placing orders we regret we cannot do this, as we are trustees of the public purse and we do not consider that aeroplanes will be of any possible use for War purposes."

That was in fact just 47 years before our Guest of Honour, Mr. Sandys, you will remember said the same thing again:—

"We do not consider that aeroplanes will be of any possible use for War purposes"—in his White Paper of 1957.

In the interim the British Aircraft Industry had built some 175,000 aeroplanes, most of them for War purposes, and had been paid some £4,000 million for doing so. Out of this more than £1,000 million worth of aeronautical products have been exported over 50 years.

So on the whole, I think that those who got turned down in 1910 can feel that "the end result" was tolerable. I hope that we shall continue to feel the same, say, 50 years hence.

Sir Walter Raleigh—the great Air historian—writing in 1918 described 1910 as a year of "adventure and progress, of danger and disaster. Records were made and broken so fast that the heroic achievement of the Spring became the average performance of the ensuing Autumn. The Aviation Movement was fairly under way—and nothing could stop it."

Indeed, it was said that "the World was moving so fast that the man who said that something could not be done in Aviation was generally interrupted by somebody doing it".

There were even plans to fly the Atlantic.

Those days can be summed up by saying that "an immense service was rendered by 'gentlemen adventurers', engineers and pilots who—all for love—and nothing for reward, built machines and flew them."

Among them, when the storm broke in 1914, the names Sopwith, de Havilland and Handley Page, stood out from a list crowded with distinction and achievements.

The great C. G. Grey remembered men, "possessors of comfortable incomes, who lived for years on thirty or forty shillings a week and spent the rest on their aeroplanes."

"It was a society"—says Raleigh—"like the early Christians: it practised fellowship and community of goods."

And, like the early Christians, people in aeronautics have been used to being "thrown to the lions" ever since.

1910 was the year in which Grahame-White and Paulhan raced from London to Manchester, Charlie Rolls, Tom Sopwith and Cecil Grace flew across the Channel and Robert Loraine flew across the Irish Sea.

And, towards the end of the year, the Bristol Company—after sending an aeroplane to be demonstrated in India, and selling eight aeroplanes to Russia (the first export) made also the first agreement with the War Office—in spite of the previous discouragements—and set up a row of sheds at Larkhill.

The Bristol School at Larkhill did much to convert the Army—and it brought Geoffrey de Havilland to Farnborough.

There is so much more that could be said. But this is a lunch not a history review. Enough to say that 1910 was the year of the flowering of aeronautics in England—just as 1909 had been the year for France.

1910 was for Britain a year of restless activity and of solid achievement. I hope, in retrospect, that we shall be able to say the same of 1960.

And I think that I can say that, all through these fifty years, since 1910, the Royal Aeronautical Society has maintained its position as the general forum for aeronautical thought and discussion on the scientific, the engineering, the research and the practical operating sides, of all aspects of Aviation.

One of the most encouraging things of recent times—looking ahead—has been the tremendous success and activity of the Astronautics and Guided Flight Section of the Society under the Chairmanship, first of Sir George Gardner and now, Mr. Val Cleaver.

Also we now have the merger with the Society of the Helicopter Association of Great Britain, which will carry on as the Rotorcraft Section.

At the other end of the scale—and no less scientific in its endeavour—is the Man Powered Aircraft Group. This Group aims to achieve controlled and sustained flight by man power alone—for the first time in history. It will need refined aerodynamics, sophisticated structures and good mechanical engineering if it is to succeed.

It is an example of real sporting endeavour and I am delighted that Mr. Henry Kremer, who has personally presented a £5,000 prize for an officially observed man-powered flight of a mile over a figure of eight course, is with us today.

In this past year, thanks to the generous support of individual members and both the Industry and the Operators, the Royal Aeronautical Society has been able to embark upon the building of a Lecture Theatre at its headquarters at 4 Hamilton Place.

This new Lecture Hall—initiated appropriately by my predecessor—Sir Arnold Hall—will be opened in October of this year, in the Presidency of my successor—Eric Moult.

For the first time it will give, here in the centre of the Commonwealth, a centre for all aeronautical debates and lectures and discussions and meetings generally.

Already there are more than 100 bookings for meetings next year. And I would like to acknowledge here the Council's gratitude for the support which has made this work possible for the benefit, not only of the Society, but all other branches of Aviation as well.

This Lecture Theatre will indeed give us a focal point at which the scientific and engineering problems of the decades ahead can be hammered out on aeronautical territory.

The past decade—"The Nineteen Fifties"—brought us turbine air transport—both the turbo-prop and the jet. It brought us Man's first adventure into Space. And it brought us guided missiles and the sight of the end of manned strategic aircraft for military purposes. And it brought us a Minister of Aviation.

I think we can take some pride in the fact that in this past decade of the "Nineteen Fifties," Britain had many "Firsts" in pressing forward on the frontiers of aeronautical knowledge.

But, we in British Aviation—in this Society—must not just look back. Indeed, our looking back must only be to learn lessons for the future.

Our eyes, our minds, and our endeavours must all be looking ahead—into the future.

At this point, indeed, as we enter the "Nineteen Sixties," we find our aeronautical business at a cross roads. And the man who is directing the traffic is Mr. Duncan Sandys.

For the first time in Government history we have a Minister of authority with a seat in the Cabinet, concerned solely with Aviation.

This is a major step forward in the recognition of the importance of aeronautics for the future of our country.

In his thinking ahead we know that the Minister's attention is concentrated initially on the vital problems of the aircraft manufacturing industry and the air transport operating industry. We trust that it will be focused too on the much neglected field of business and sporting Aviation, in which this country led the World before the War but has fallen sadly behind since then.

Government policy towards landing fields (the ports at which our "little ships of the air" can dock) is fundamental also to that issue.

Perhaps most important of all is to establish in the Nation as a whole, faith in the future of British aeronautics, so that it will continue to attract those men of intellect, imagination and vigour, who have kept our country to the fore through the past 50 years.

Let us hope that—in the years to come—with a sure hand at the helm, through a Ministry and a Minister devoted to Aviation, we shall see our national position maintained in aeronautics, as it has been on the seas in days gone by.

Already I think we can say that Mr. Sandys echoes a variation of Sir Winston Churchill's words—that he was "not appointed to his high office to preside over the dissolution of the British Aircraft Industry." Recent events may, we hope, bring strength to the future.

And so, in looking ahead let us do so with faith, and with hope, and with optimism.

We shall take the optimistic view and, although individually, we of the Royal Aeronautical Society may be closely concerned with some of the "dynastic marriages" which are being arranged, in fact, as a Corporate Body we are concerned rather with the broader issues of long-term effect.

The manufacturers and the operators who implement the policies are, indeed, only instruments of a much bigger whole.

Yet, one sometimes feels that the controversial noise of the jets at take-off is almost drowned today by the, even more controversial, noise of the grinding of axes at take-over.

One can only hope that what has been done—and what will be done—will be for the good of the future of British Aviation in all its aspects, and that it will turn out well.

We of the Society are concerned only with the broad future of British Aviation and that its long-term well-being—which can mean so much to the World at large—shall be planned soundly.

So, all of British Aviation, in which so many of us have spent our lives, now rests in the hands of Mr. Sandys and his advisers. God give them strength.

As usual, Shakespeare had the words for it. He wrote:—

"Duncan has been so clear, in his great office
That his actions will plead like angels, trumpet-tongued
Against the deep damnation of his taking-off
Striding the blast upon the sightless couriers of the air"

this last—obviously a reference to guided weapons.

In 1919, a great feat in aeronautics was achieved, for the first time, by British Aeronauts. His Majesty's Airship R34 made the first double crossing of the North Atlantic ocean by air.

I mention that because just 40 years ago, Rudyard Kipling—who is now being rediscovered as "a great British poet"—wrote a letter from "Bateman's Burwash", in Sussex, to a Member of this Society, General Edward Maitland, who commanded the R34. Kipling said in this letter of 1920:—

"You, and everyone on board, must have felt that you stood at the opening verse of an opening chapter of endless possibilities."

That, Minister, is where we all believe we stand today—"at the opening verse of an opening chapter of endless possibilities."

So, in celebrating these two anniversaries, 1866 and 1910, may I couple also one other—the arrival of a day in January 1908—its anniversary now only a few days off—which was the birthday also of—Our Guest of Honour.

Minister, in more senses than one, the World looks towards you.

At this opening chapter of the new decade—so full of portent for aeronautics—I give you the toast of **"British Aviation"** and I couple it with Her Majesty's Minister of Aviation, **Mr. Duncan Sandys.**

MR. SANDYS' REPLY

The Minister of Aviation, the Rt. Hon. Duncan Sandys, M.P. : It is a privilege to be here to-day with some of the pioneers whose famous names will forever be honoured in the history of aviation. It is difficult to say exactly when flying started; but it seems clear that your Society was the first learned body in the world set up to deal with the science of aeronautics. At your first meeting, in 1866, Francis Wenham presented his classic paper entitled: "Aerial Locomotion and the laws by which heavy bodies impelled through the air are sustained." That was undoubtedly one of the starting points of modern aviation.

From the beginning of this century, the Government of the day has been closely associated with the development of the aeroplane; and the alleged frustration of Treasury control, of which some of you occasionally complain, is nothing new. For example, I find that, in 1909, the head of the Military Ballooning Establishment at Farnborough, as it was then called, was ordered to discontinue experiments with aeroplanes. It was explained that the Government had already spent over £3,000 on this idea, and that it was not considered justifiable to risk any further public money on so doubtful a project. To-day, the Government spends well over £300 million a year on various aspects of aviation; and as before there are many who still think that that is not enough.

Mr. Duncan Sandys delivering his speech. The President can be seen on the Minister's left and, behind the microphones, The Minister of Labour, the Rt. Hon. Edward Heath, M.P.

In all spheres there are doubters, but in aviation even the most enthusiastic believers have been surprised by the pace and the extent of the progress made.

Twenty years ago, few would have predicted that more people would now be crossing the Atlantic by air than by ship. This afternoon, throughout the world, there will be about 40,000 passengers in the air and, if it were July instead of January, there would be twice that number. Nobody doubts that air traffic will continue to expand; and it is quite likely that, once again, progress will be much faster than is now thought possible.

Civil and military aviation have, from the beginning, been closely bound up together, and Government expenditure on military types has provided a powerful impetus to developments on the civil side.

Three years ago, as Minister of Defence, I decided that we must cut down expenditure on military aircraft. The implications of this decision were sensationally exaggerated in many quarters. It was said that this implied the end of piloted flight in the Services and that there was to be a complete change-over to push-button warfare. As I explained, we had, of course, no such intention. Manned aircraft will continue to be needed by the Services for many important roles as far ahead as one can see.

On the other hand, the advent of guided weapons and ballistic rockets to fill roles hitherto performed by aircraft, obviously made it necessary to reduce the number of new military aeroplanes to be developed. While this policy was criticised at the time in some circles, it is interesting to note that other major Powers, including the United States, are now having to face the same decisions.

It is nevertheless clear that, if Government support for aeronautics through Military channels is reduced, there is a case for making some increase in the assistance given on the civil side. That is what we are proposing to do. I have recently been discussing this matter with the industry; and I hope shortly to make an announcement of our policy.

On the occasion of the 94th anniversary of your Society, it is natural for us to look back with pride upon the remarkable progress achieved. But this is also an occasion to peer a little into the future and attempt to discern the likely course of things to come.

In the years ahead, we can look forward to important technical advances in propulsion, aerodynamics, electronics and materials. Among the practical results, the most spectacular, though perhaps not commercially the most important, is likely to be the increase in speed. There is little doubt that in the 1970s long range civil air liners will be flying at two or three times the speed of sound.

The cost of supersonic transport aircraft will be very heavy indeed, but this should be largely offset by the increased frequency of the journeys, which high speed will make possible. In fact, the passenger-carrying capacity of such an aircraft should compare well with that of a large Atlantic liner. The *Queen Elizabeth* carries about 2,000 passengers and makes about 45 crossings a year. On the other hand, a supersonic aircraft carrying 100 passengers and taking two or three hours could make a thousand crossings in a year. Thus, a single aircraft could carry as many passengers as an 80,000 ton ocean liner.

Apart from increased speed, continued improvements in the design of aircraft and in the efficiency of aero-engines should steadily reduce operating costs. This should lead to a progressive cheapening of passenger fares and should make it commercially feasible to carry much more freight by air. These various factors, together with the constantly rising standard of living of the world, will assuredly stimulate an immense growth in air traffic. It is generally expected that the number of passengers will double in the next five to eight years. By 1980, it is possible that ten times more people will be travelling by air.

If traffic expands at anything like this rate, the world's existing airports will become completely choked; and this kind of traffic problem is not one which can be solved by "Pink Zones" or parking meters. Nor shall we solve it merely by building more aerodromes and runways around the great cities. For we shall need not only more room on the ground, but also more room in the sky.

There will have to be major advances in air traffic control, so that many more aircraft can be handled simultaneously in the limited air space available. At the same time we must bring in fully automatic landing techniques, which will make it possible to fly safely in all weathers.

We must also press ahead with the development of passenger aircraft which can land and take off vertically, or nearly so, and can therefore operate from small dispersed sites. The technical problems involved are now pretty well understood, but a very big effort will be needed before this can be made a commercial proposition.

I have spoken so far about aircraft. I should like now to say a word about rockets. In an early flight of fancy some three hundred years ago, Cyrano de Bergerac thought of travelling to the moon with the help of magic bottles of dew, which would provide lift by evaporation. As another possible method of transport, he conceived the idea of an iron chariot, drawn forward by magnets thrown out in front by the driver. Alternatively he suggested, more prophetically, that it might be propelled by rockets.

Fact has now replaced fiction. Russia and America have taken the first dramatic steps in the exploration of outer space. Britain's effort in this field has so far been confined to firings in Australia of Skylark, a research rocket which has made observations in the upper atmosphere, at heights up to 100 miles. We have also made a valuable contribution to scientific knowledge through the observation of other people's satellites. As a result, British scientists at Farnborough discovered that the earth's top and bottom are less flat than had been thought. That is a piece of information which will, no doubt, be very important to the penguins, though they probably knew all about it long ago.

The time has not yet come to decide whether Britain should undertake an independent programme of space exploration; for without a British ballistic rocket, we are not in a position to project satellites of our own. However, we have already developed a most valuable experimental rocket, Black Knight, which has reached a height of 500 miles. It is worth noting that the first five firings were all of them successful—an almost unique technical achievement. Apart from its separate use as a research vehicle, Black Knight could provide a second-stage rocket to go on top of our ballistic rocket Blue Streak, which we have now been developing for several years.

A combination of Blue Streak and Black Knight with a small additional rocket stage could, if we wished, provide the thrust needed to put a satellite of nearly one ton into orbit round the earth, or to project a weight of 200 lb. to the moon. The accuracy of Blue Streak should also be fully sufficient for this purpose, since the precision needed for hitting a target on the earth's surface is about twenty times greater than is required to hit the moon.

It is too early to assess the practical benefits which may be derived from space exploration. But, if past experience in other fields is any guide, they are likely to be far greater than can now be foreseen.

One possible use may be in connection with radio. Earth satellites, used as passive reflectors of radio signals or as relay stations, might well provide a large number of channels for telephone communications and no doubt for television as well. This is a problem to which British industry might well begin to address its mind.

Other applications of satellites include weather observation and possibly, in the dim future, some system for controlling the weather itself.

I doubt very much whether it will be thought worthwhile to develop the ballistic rocket as a means of carrying fare-paying passengers from one part of the earth to another. Apart from the discomfort of violent acceleration and deceleration, the intense heating during re-entry into the atmosphere presents a very serious problem, not to mention the difficulty of landing the rocket gently at the other end. Some of these problems could perhaps be solved by using a hypersonic rocket-boosted glider, which I am told might travel at ten times the speed of sound half way round the world without refuelling.

Within our lifetime, the stupendous advances in aeronautics and their application to peaceful and warlike purposes have altered the face of the world. They have brought us great benefits and also great misfortunes; and we have only a vague conception of the incalculable possibilities which lie ahead.

It now seems virtually certain that human beings will be able to travel to the moon and far beyond. I only hope that we shall make good and honourable use of these momentous opportunities. Looking out upon these boundless new horizons, let us pray that, before moving onto other planets, the inhabitants of this Earth will feel inspired to establish peace and goodwill among themselves.

The following were among the members and guests present at the luncheon:—

J. Aherne-Heron, J. A. Airey, J. E. Allen, Mrs. H. G. Alston, Mr. and Mrs. E. F. Anderson, F. A. Axleby, Dr. A. M. Ballantyne, A/Cdre. and Mrs. F. R. Banks, E. G. Barber, Miss F. E. Barwood, E. L. Bass, William Bates, Air Vice Marshal Bateson, G. B. Bathurst, A. D. Baxter, J. C. Beadle, W/Cdr. R. P. Beamont and Guest, Mr. and Mrs. G. E. Beck, Prof. and Mrs. J. A. J. Bennett, Dr. K. G. Bergin, F. Beswick, L. Boddington, G. W. Bone, L. A. Booty, Mr. and Mrs. C. L. Bore, M. H. Botten, Ivor Bowen, E. C. Bowyer, Lord Brabazon of Tara, Mrs. J. Bradbrooke, J. R. Bradford, G/Capt. A. F. Britton, Capt. and Mrs. L. Broadhurst, A/Cdre. H. le M. Brock, P. W. Brooks, D. L. Brown, R. S. Brown, H. Buckingham, Major G. P. Bulman, Sir Aubrey Burke, Mr. and Mrs. H. D. Burke, Mrs. V. Burt, Viscount Caldecote, Sir Sydney and Lady Camm, T. W. Campbell, H. Caplan, Air Vice Marshal D. V. Carnegie, Dr. and Mrs. W. Cawood, L. F. Chambers, J. M. Chapman, John Chappell, Dr. I. C. Cheeseman, Mrs. M. E. Cheeseman, A. Chinneck, R. M. Clarkson, A. V. Cleaver, F. J. Cleveland, Air Vice Marshal Sir Ralph Cochrane and Guest, Dr. R. Cockburn, R. A. Cole, Prof. and Mrs. A. R. Collar, D. C. Collins, J. V. Connolly, A. N. Councell, C. L. Cowdrey, Sir Harold and Lady Roxbee Cox, H. S. Crabtree, G. G. Craddock-Watson, F. W. Crews, J. Cuming, R. L. Cumming, H. B. Cundall, M. H. Curtis, M. M. V. Custance, A/Cdre and Mrs. C. L. Dann, B. Davidson, E. G. Davidson, R. H. Davidson, B. D. Davies,

Handel Davies, S. D. Davies, N. J. A. Deaton, K. C. Derrick, P. H. C. Dickens, A. C. Dickinson, Geoffrey Dorman, Lord Douglas of Kirtleside, Capt. R. Duffield, E. Duggan, Mr. and Mrs. C. Dykes and Guests, Mr. and Mrs. R. M. Eden, Sir George and Lady Edwards, Sir Gerard d'Erlanger, W. M. Evans, P. J. Farmer, W. R. Farnes, W/Cdr. and Mrs. R. J. C. Farrell, Sir William Farren, K. Fearnside, Sir Roy and Lady Fedden, C. R. Field, B. W. Firth, L. Florendis, Air Chief Marshal Sir Francis Fogarty, D. Follows, Dr. G. A. Forester, W/Cdr. S. T. Freeman, L. G. Frise, Mrs. S. O. Frise, R. W. G. Gandy, Sir George and Lady Gardner, H. H. Gardner, Dr. J. B. Gardner, Sir William Garthwaite, S. B. Gates, Mr. and Mrs. L. J. Geering, H. Giddings, H. Goodrich, Mr. and Mrs. H. Goodwin, Mr. and Mrs. R. Graham, L. S. Greenland, Capt. L. B. Greenstead, A. H. C. Greenwood, J. A. Grieveson, R. Griffiths, A. Grimes, R. G. Grout, Sir Charles Guest, G. L. Hack, Mr. and Mrs. R. Hafner, A. E. Hagg, H. 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Thurston, Mr. and Mrs. E. Trees, Capt. C. Turner, R. Turnill, W. Tye, Sir Frederick Tymms, F. Tyson, C. F. Uwins, Mr. and Mrs. V. C. Varcoe, Sir Reginald Verdon-Smith, J. B. Waite, Sutherland Waite, E. Manley Walker, G. Wansbrough-White, Mr. and Mrs. P. Ward, Dr. E. Warlow-Davies, W. Webb, N. J. L. Webber, R. H. Weir, G. Wharton, E. C. Wheeldon, A/Cdre. and Mrs. A. H. Wheeler, Capt. Q. P. Whitford, A. J. Whittemore, Mr. and Mrs. D. M. Wiggins, P. A. Wills, D. L. Hollis Williams, J. A. C. Williams, J. W. Williams, Mr. and Mrs. L. Williamson, R. Wilson, Mr. and Mrs. L. A. Wingfield, H. T. Winter, L. J. Cardew Wood, Mrs. V. M. Cardew Wood, Mr. and Mrs. R. H. Woodall, E. A. C. Wren, G/Capt. S. Wroath, Mr. and Mrs. P. R. Wyke, D. Wyndham-Smith.

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Reviews

HANDBOOK OF AUTOMATION, COMPUTATION AND CONTROL. *E. M. Grabbe, S. Ramo, D. E. Wooldridge (Editors).* Volume II. *COMPUTERS AND DATA PROCESSING. *Chapman and Hall, London, 1959. 1,030 pp. Illustrated. £7.*

Like the first volume of this three volume work, this book of over 1,000 pages contains contributions from upwards of 40 different authors. Three-quarters of the book is concerned with the design and programming of digital computers, the remainder being devoted to analogue machines.

After a short glossary of computer terminology, there follows what is virtually a self-contained treatise on digital computer programming contributed by John W. Carr, III. Anyone who heard Dr. Carr speak at the recent British Computer Society Conference will know him to be an enthusiastic advocate of automatic programming and he has devoted considerable space to that topic in the present text. While the section succeeds in giving a general picture of current American trends in programming techniques, even the experienced programmer will find it hard going. Sixty pages are devoted to summaries of the instruction codes of common American machines, while much of the rest consists of detailed examples showing the use of various symbolic programming techniques. One cannot help feeling that much of this detail is only of interest to a few specialist programmes, and that in any case it will be out of date in a relatively short time.

After the coding details and complex symbolic logic of Dr. Carr's section, it is something of a relief to turn to the next part of the book, which deals with the use of digital computers and data processing machines. This section has a strong commercial bias. While there is a very inadequate chapter of only 12 pages on "engineering and scientific applications," considerable space is devoted to giving general information about commercially available data processing equipment, parts of the text being at the manufacturer's catalogue level. To quote an apparently serious comment from the section on planning the layout of an installation—"Most installations have provided viewing rooms for visitors. It has been found desirable to place the more dramatic and impressive units of equipment, such as the printing devices, monitoring panels, and magnetic tape units close to and facing out towards the viewers."

The next section is concerned with the design of digital computers. There are chapters on logical design, circuitry, storage systems, and input-output equipment, all these topics being dealt with in considerable detail. There are even drawings showing mechanical details of devices such as electric typewriters and teleprinter punches.

The final section is concerned with the design and application of analogue computers. There are detailed discussions on both linear and non-linear electronic circuit elements, with examples showing how they can be combined to solve a variety of different problems. There is also a chapter on the solution of field problems and another on mechanical analogue devices. The final chapters of the section discuss analogue-digital conversion, and systems which combine both analogue and digital elements.

Like Volume I of the series, the work is essentially a reference book—it is almost impossible to read it section by section as one would a textbook. A good index is therefore essential, and this is provided. At the price quoted, however, one wonders how many people will wish to purchase such a heterogeneous collection of information.
—R. K. LIVESLEY.

*For review of Volume I (Control Fundamentals) *see* the December 1959 JOURNAL, p. 738.

THERMODYNAMICS. *Gordon J. Van Wylen. John Wiley, New York (Chapman and Hall, London), 1959. 567 pp. Illustrated. 64s.*

So great has been the flood of text books in the field of thermodynamics in the past few years that the reviewer may be excused for tending to flinch when yet another is presented. It must be stated at once that, in this case, it would have been unfortunate if such an initial reaction had led to this book being dismissed as just another rehash of Keenan's work. Van Wylen has clearly crystallised in this book much of his own experience in the teaching of engineering thermodynamics. He has brought to this work a clarity of thought and a desire to tackle the real difficulties that is quite refreshing.

It could well be argued that the title is too wide, for this book is written with engineering applications very much in mind even though the theoretical treatments are sufficiently rigorous to satisfy all but the most pedantic. The book contains little purely descriptive matter and the first chapter, which describes a few practical thermodynamic devices, seems somewhat out of place and, as an hors d'oeuvre, somewhat inadequate. However the subsequent detailed analysis—which occupies about half of the book—of the laws of thermodynamics and their implications is very well presented.

Power and refrigeration cycles are treated in a single long chapter with little emphasis on practical considerations. In particular, it might well be considered that refrigeration is treated somewhat lightly. The section on flow through nozzles, orifices and through blading is adequate from the non-specialist point of view, but the concluding chapters on Maxwell's relations, equations of state and on chemical reactions and equilibrium are perhaps too brief.

In general, this book should prove very helpful in introducing undergraduate students to the fundamentals of thermodynamics. The extensions of these considerations into specialist fields are presented logically but the depth of treatment in a book of this length has necessarily had to be somewhat limited.—H. BILLETT.

THEORY OF ELASTICITY. *L. D. Landau and E. M. Lifshitz, translated from Russian by J. B. Sykes and W. H. Reid. Pergamon Press, London, 1959. 134 pp. Illustrated. 40s.*

This book is the English translation of Vol. VII of a comprehensive course on Theoretical Physics sponsored by the U.S.S.R. Academy of Sciences.

Though the book contains plenty of mathematics, the approach is physical rather than mathematical and the subject matter, as shown by the four chapter headings,

Fundamental Equations, The Equilibrium of Rods and Plates, Elastic Waves and Thermal Conduction and Viscosity in Solids, includes several topics that are not normally contained in an English book having a similar title, and excludes much that one would normally expect to find. In particular, there is no reference to the behaviour of beams or cylinders under forces or couples applied at their ends, no mention of the complex variable methods developed by Muskhelishvili in Russia and Stevenson in this country for solving two-dimensional problems, and the treatment of stability is confined to the buckling of struts.

The book is designed to be read right through by students, not just referred to as a work of reference, and an interesting feature is the inclusion of a substantial number of problems *together with* sketch solutions.

Having regard to its purpose, the book is well constructed, ably translated, and excellently produced, although at 40s. it is perhaps, rather expensive.—D. M. A. LEGGETT.

AIRCRAFT AND MISSILE PROPULSION—VOL. II. *M. J. Zucrow. John Wiley, New York (Chapman and Hall, London), 1958. 636 pp. Illustrated. 104s.*

This book is the second of Professor Zucrow's trilogy on Thermodynamics, Performance and Components. It comprises chapters 6-10 of the complete work, and treats: Gas-Turbine Power-Plant Cycles and Analysis of Ideal Cycles (pp. 1-68); Analysis of Gas-Turbine Power Plants and the Turbo-prop Engine (pp. 69-185); The Turbo-jet Engine (pp. 186-345); The Ram-jet Engine (pp. 346-418); and Rocket Jet Propulsion (pp. 419-590). Problems are given on pp. 591-604 and tables on pp. 605-622.

Like the first of the trilogy, this second volume is vividly written, makes no more than reasonable demands, for the most part, on the mathematical equipment of the graduate reader, gives quite full derivation of most of the equations used, and teems with examples, references, worked examples and background information. It is admirably printed and bound.

The treatment is detailed, and the conscientious reader will not escape proficiency in gas-turbine performance calculation, on going through the first three chapters. On pp. 72-76 the "Factors Causing Deviation of Actual Cycle from Ideal Cycle" are listed under headings *a-n* inclusive and the reader will receive a very comprehensive notion of the facts that pressure losses occur in compressors, ducting, turbines, combustion chambers and heat exchangers: that the working fluid differs from air: that air is bled to cool the engine: that the efficiency of heat exchangers is less than unity: that power is taken off to drive auxiliaries: that mechanical friction occurs, and that "A decrease in kinetic energy of 2 per cent can be expected in an impulse-turbine nozzle if the inlet temperature is sufficiently high to cause the thermodynamic equilibrium between the vibrational and the translational energies of the fluid molecules to be disturbed."

The book shows evidence of being written over a span of years, the first four chapters being earlier than the last two. Fundamental theory does not date very quickly, but lists of engines do, and the lists of "Plant" gas turbines and turbo-props on pp. 35-43 cover years up to 1953 and 1950 respectively, and so will be mainly of historical interest to the reader, though he may welcome having old friends brought to mind. More serious than this, however, there is no treatment of by-pass and turbo-fan engines. These were quite highly developed at the date (June 1958) of Professor Zucrow's preface, and it seems an important omission in so comprehensive a book. Not that the conscientious reader will not be able to work out their performance himself, from the material in the book.

The ram-jet and rocket chapters are more recent, containing references up to 1957 and 1958 respectively. The very large rocket chapter (172 pp.) provides a useful introduction to both liquid and solid fueled rocketry, and to the elementary dynamics of rocket-propelled vehicles. Looking for something off the beaten track, the reviewer went carefully into the section 13b (work accomplished by the rocket jet propulsion system) and 13c (overall efficiency of rocket jet propulsion). Professor Zucrow defines "work accomplished" as the integral of thrust with respect to distance travelled. This is a definable quantity. The trouble is, that it does not, even in the absence of gravity and drag, enter into any very simple relations with other quantities. For instance, even in the absence of gravity and drag, the "work accomplished" is not equal to the final kinetic energy of the vehicle. Section 13c goes on to define the "overall efficiency of rocket jet propulsion" as (work accomplished by the propulsion system/energy supplied in the form of fuel). This is a definition, but what does it signify? What relationship does the "work accomplished" enter into with other quantities? What has the work done? Actually it has partly given the vehicle kinetic energy, and partly given the jet kinetic energy. Is the object of a rocket to produce kinetic energy in a jet? If not, why define an efficiency which counts part of the jet kinetic energy as useful? Would it not be better to initiate the reader into the mystery that rate of increase of vehicle kinetic energy and rate of increase of jet kinetic energy is equal to the power of the jet, that is, the power that a perfect turbine sitting on the rocket could convert into shaft power? Or why not define an efficiency equal to final vehicle kinetic energy/energy supplied in the form of fuel?

In spite of the adverse nature of some of these comments, the reviewer considers the book to be well worth having. As with the first volume, the teacher and the student will find the book useful. But a careful and critical reading of some sections will be necessary.—A. G. SMITH.

SENT FLYING. The Autobiography of Bill Pegg. *Macdonald, London, 1959. 236 pp. Illustrated. 21s.*

Sent Flying is a rather unexpected title for an autobiography by Bill Pegg. It underlines the admission by the author (also rather surprising) that he really just drifted into the business of becoming a pilot after enlisting in the R.A.F. as an apprentice. Once he had been bitten by the idea of being a pilot, he went ahead rapidly, becoming a test pilot at Martlesham Heath, and, not long before the Second World War, a test pilot with the Bristol Aeroplane Company. During his period with the Company he did the prototype testing of the Brabazon and of the Britannia. The description of the Brabazon testing makes fascinating reading. The testing of the Britannia is described as never before, since, in it, Pegg tells of his unpleasant experience when he had to ditch one of the prototypes in the mud of the Severn Estuary. Unfortunately he omits the technical details of this unlucky event. He does, however, quote the full radio sequence as recorded during the flight and recreates the atmosphere of tension very clearly. In simple terms, he discusses many of the technical problems confronting a test pilot. This is an unusual book of great interest, a little untidy perhaps as regards subject matter, provoking as regards the omissions of technical detail, but well worth reading. Pegg's career is unique among test pilots and, if a criticism must be made, his book is rather too modest.—A.S.C.L.

THEORETICAL ELASTICITY AND PLASTICITY FOR ENGINEERS. *D. E. R. Godfrey. Thames and Hudson, London, 1959. 311 pp. Diagrams. 42s.*

Chapters I and II give an analysis of stress and strain in a three-dimensional body. Vector methods are used extensively and attention is given to the various stress and strain invariants. The notion of complex stress combinations is introduced. Chapter III treats briefly the pure bending of a beam by the semi-inverse method.

Chapter IV is devoted to the torsion problem, making use of functions of a complex variable. The theory includes the multiply-connected section and full solutions are given for the ellipse, equilateral triangle, rectangle, sector of circle, circle with circular groove, fluted column, cardioid and circle with eccentric circular hollow. These latter sections are characterised by the ease with which their boundaries can be represented in complex form or can be transformed conformally. Chapter V treats the bending with shear of beam of arbitrary section, with a few examples. Two-dimensional elasticity is treated in over 50 pages in Chapter VI. Extensive use is made of the theory of a complex variable and of conformal transformation. The analysis is based on the works of Muskhelishvili and Stevenson. Examples include the determination of stress concentration factors around unreinforced holes of exotic shapes. Chapter VI ends with a brief theoretical account of photoelasticity.

Solutions of the basic equations in cylindrical polar, spherical polar and bipolar co-ordinates are given in Chapter VII; examples include the torsion of a conical shaft and the cylinder with an eccentric hollow under pressure.

In Chapter VIII the method of complex potentials is used to study the effect of concentrated forces and moments on the boundaries and inside a plane sheet. Attention is directed to tip forces on a wedge and more general loading on the boundary and inside a half-plane. Vector analysis is used in determining the effect of boundary loads on a semi-infinite space.

Chapter IX treats the classical small deflection theory of plates, the basic equations again being derived from the mathematician's standpoint rather than the engineer's. Engineers unfamiliar with Stevenson's work will find the notation here difficult; for example $\overline{xx}$ is a *torsional couple*, and P is the *plate modulus*. The method of complex potentials is used to solve the pure bending of infinite plates containing unreinforced holes of various shapes, for which the analysis is similar to plane stress problems.

Finally, the author treats plasticity and introduces the Reuss and Mises equation. Simple examples are given on plastic bending of a rectangular beam, plastic torsion of a circular cylinder and expansion of a thick-walled cylinder. Galin's plastic-elastic solution is given, use being made again of complex potentials.

Most of the chapters end with a few problems of a mathematical nature and the author includes Appendices on mathematical methods (including vectors) and function of a complex variable.

The title of the book will strike many, including the reviewer, as misleading in its reference to engineers. The author's approach to the subject and his presentation are those of the mathematician, and it is to the applied mathematician that the book may appeal. Finally, it should be noted that the accent throughout is on *exact* methods of solution; no mention is made of the powerful but approximate methods based on energy theorems that are normally the engineer's stock in trade.—E. H. MANSFIELD.

Additions to the Library

Advances in Aeronautical Sciences. Volumes I and II. T. von Kármán, Chairman of Editorial Committee. Pergamon. 1959. 1,144 pp. Illustrated. £10 for two volumes. *To be reviewed.*

Aircraft Ice Protection Conference. D. Napier and Son Ltd. 1959. The Lectures and Discussions held at Luton on 9th June. Five papers, separately paginated, by English and American authors.

Fighter Command. Peter Wykeham. Putnam, London. 1960. 320 pp. Illustrated. 30s. *To be reviewed.*

Flames; their Structure, Radiation and Temperature. 2nd Edition. A. G. Gaydon and H. G. Wolfhard. Chapman and Hall, London. 1960. 383 pp. Illustrated. 70s. In the review of the first edition (p. 661, October 1953 JOURNAL) it was pointed out that parts of this book might become out of date fairly rapidly because "the subject matter of this stimulating book represents a field in which much research is being done." The second edition has now appeared and its aim is still "to give a fairly advanced discussion of a part of the field that is concerned with stationary flames, with the emphasis on the physical rather than the chemical viewpoint." Much new material is included, covering information that has become available from the Fifth, Sixth and Seventh International Combustion Symposia, and one of the two completely re-written chapters is on combustion processes of rocket-type fuels.

Hearing before the sub-committee on Research and Development of the Joint Committee on Atomic Energy: First session on the Aircraft Nuclear Propulsion Program. U.S.G.P.O. 1959. 418 pp. 11s. 3d. (from H.M.S.O.). **Report of the Joint Committee on Atomic Energy,** Congress of the United States. U.S.G.P.O. 1959. 25 pp. 1s. 5d. (H.M.S.O.). These two items are complementary.

Hurricane Story, The. Paul Gallico. Michael Joseph, London. 1959. 144 pp. Illustrated. 12s. 6d. A short "storybook" of the Hurricane—certainly not a documentary.

Minimum Weight Analysis of Orthotropic Plates under Compressive Loading. George Gerard. The University College of Engineering, New York. 1958. 19 pp. No price. Various forms of stiffened plate construction considered for use as the compression covers of multicell wing box beams are presented.

Origins of the Aircraft Propeller, The. C. H. Gibbs-Smith. Rotol. 1959. Extracts from three numbers of the house journal of Rotol and British Messier. Traces the history of the propeller from da Vinci.

Petroleum Handbook. 4th Edition. Royal Dutch/Shell. Shell International, London. 1959. 677 pp. Illustrated. No price. The fourth edition of this well-known educational handbook, written and produced by members of the Shell staff, is the latest to appear since 1948. The parts of the book dealing with petroleum chemicals and with research have been considerably enlarged, reflecting the expansion of the Company's interests. The whole volume is larger and the presentation could hardly be improved. The use of colour in the diagrams and of first-class paper and printing make this new edition a pleasure to use and handle.

Random Vibration. S. H. Crandall (*Editor*). Second Edition. M.I.T., John Wiley, New York (Chapman and Hall, London). 1958. 423 pp. Figs. 68s. Originally published in 1958 in a paper bound edition in connection with the M.I.T. Special Summer Program on Random Vibration. The eleven papers, all from the United States, cover mechanical vibrations with deterministic excitation, random processes, stochastic processes of mechanical origin, statistical properties of response to random vibration, structural damping, fatigue of metals, instrumentation for random vibration analysis the effect of random pressures and noise on structures and missiles, simulation equipment and mechanical design for random loading.

Similarity and Dimensional Methods in Mechanics. L. I. Sedov. Cleaver Hume, London. 1959. 363 pp. Diagrams. 5 gns. *To be reviewed.*

Small Gas Turbines. Arthur W. Judge. Chapman and Hall, London. 1960. 328 pp. Diagrams. 48s. *To be reviewed.*

S.A.E. Preprints

(Annual Meeting, Detroit, Michigan, 11th-15th January 1960)

No.

128A F-106 multiple power generating system. P. W. Corbett and R. K. Walter.

128B The integration of a constant speed drive with a weapon system. A. V. Chavel and J. L. Burgess.

128C Specification requirements for U.S.A.F. engine driven constant speed alternator drives. R. A. Novotny.

128D Constant speed drive starter units. P. R. Wood.

128E Matching a constant speed drive to a specific application. C. D. Flanigen.

128F Design of hydro-mechanical constant speed drive for a 120KVA generator. P. C. Mosher and L. B. Hallberg.

128G Design and performance of constant speed drives for commercial use. R. H. Guedet.

133A Basic principles of ground cushion devices. G. D. Boehler.

133B Sliding on air. A.L. Haynes and D. J. Jay.

133D The case for an ocean-going ground effect machine. H. R. Chaplin.

136A Up in the air with business. H. W. Boggess.

136B A small company uses airplanes. G. F. Drake.

136C General aviation during the soaring sixties. D. Roskam.

138A Integration of missile ground support equipment. I. Trowbridge and W. B. Van Horne.

138B Launcher shelters for Bomarc. R. V. Ostling and P. M. Kelly.

139A Surge characteristics of aircraft underwing fuelling—a by-product of pressure fuelling. R. H. K. Cramer and D. L. Davis.

139B Landing gear and tire experience with the Boeing 707. W. P. Erickson.

I.A.S. Preprints presented at **28th Annual Meeting**
(New York, 25th-27th January 1960)

No.

60-1 Observations of hail storms by means of airborne radar. L. J. Battan.

60-2 A basis for the prediction of severe local thunderstorms. D. C. House.

60-3 The occurrence of damaging hail at high altitudes. H. S. Appleman and P. E. Lehr.

60-4 Some aspects of non-equilibrium flows. R. Sedney.

60-5 One dimensional flow of a gas-particle system. J. R. Kliegel.

60-6 Fluctuating lift and drag acting on a cylinder in a flow at supercritical Reynolds numbers. Y. C. Fung.

60-7 Some aspects of designing aluminium structures for thermal environments. J. M. Card and A. B. Burns.

60-8 Heat protection by ablation. R. M. Wood and R. J. Tagliani.

60-9 The introduction of creep into structural analysis. C. Riparbelli.

60-10 Ultrasonic welding and improved structural efficiency. J. B. Jones and H. L. McKaig.

60-11 Rapid crack growth in sheet structure. E. J. Zapel.

60-12 Static and fatigue strength of metals subjected to triaxial stresses. W. M. Lehrer and H. Schwartzbart.

60-13 The propulsion aspect of ground effect machines. R. W. Pinnes.

60-14 Over-water aspects of ground-effect vehicles. R. E. Kuhn *et al.*

60-15 Potential of the air-cushion vehicle. R. P. Jackson and M. F. Southcote.

60-16 Utilization of the pilot in the launch and injection of a multistage orbital vehicle. E. C. Holleman *et al.*

60-17 The use of rotors for the landing and re-entry braking of manned spacecraft. C. R. Haig.

60-18 Development of lateral-directional flying qualities criteria for supersonic vehicles, based on a stationary flight simulator study. R. M. Crone and R. C. A'Harrah.

60-19 Some observations on supersonic stabilization and deceleration devices. J. F. Connors and J. C. Lovell.

60-20 Supersonic boom of wing-body configurations. I. L. Ryhming and Y. A. Yoler.

60-21 Flexural vibrations of a rectangular sandwich panel. C. C. Chang and B. T. Fang.

60-22 Supersonic panel flutter of a cylindrical shell of finite length. M. Holt and S. L. Strack.

60-23 Cryogenic propellant storage for round trips to Mars and Venus. G. R. Smolak and R. H. Knoll.

60-24 Considerations in the design of chemical rocket powerplants for space applications. S. Lehrer.

60-25 A review of the distribution of wind and temperature in the lower stratosphere. H. A. Panofsky.

60-26 Inviscid flow with non-equilibrium molecular dissociation for pressure distributions encountered in hypersonic flight. M. H. Bloom and M. H. Steiger.

60-27 Research and design progress toward high performance rotary wing aircraft. P. L. Michel.

60-28 Dynamic absorbers in the rotating system of helicopters. R. R. Lynn.

60-29 On the methods and economics of recovering boosters for orbital vehicles. P. R. Shipps.

60-30 Propulsion requirements of a manned lunar mission. D. E. Serrill and H. J. McClellan.

60-31 Electric energy sources and conversion techniques for space vehicles. V. C. Wilson.

60-32 Dynamic airloads and aeroelastic problems at entry Mach numbers. G. Zartarian *et al.*

60-33 Some considerations of the laminar stability of incompressible, parallel time-dependent flows. S. F. Shen.

60-34 Mercury capsule and its flight systems. M. A. Faget and R. O. Piland.

60-35 Review, scope and recent results of Project Mercury research and development program. A. C. Bond and A. B. Kehlet.

60-36 Review of the operational plans for Mercury orbital mission. C. W. Mathews.

60-37 The aerodynamic appraisal of STOL/VTOL configurations. R. J. Vidal *et al.*

60-38 Boundary layer displacement and leading edge bluntness effects in high temperature hypersonic flow. H. K. Cheng *et al.*

60-39 Pebble bed nuclear reactors for space vehicle propulsion. M. M. Levoy and J. J. Newgard.

60-40 Satellite systems for commercial communications. J. R. Pierce.

60-41 A generalised study of propulsion systems for VTOL aircraft. P. W. Pratt *et al.*

60-42 A propulsion system for reconnaissance aircraft. J. F. Sutton.

60-43 The cost of VTOL. K. B. Gilimore.

60-44 Some observations on the dynamic behavior of extremely flexible rotor blades. R. L. Goldman.

60-45 The effect of an external supersonic flow on the vibration characteristics of thin cylindrical shells. H. M. Voss.

60-46 Heat transfer, recovery factor and pressure distributions around a circular cylinder normal to a supersonic rarefied-air stream. O. K. Tewfik and W. H. Giedt.

60-47 Rocket grenade measurements of temperatures and winds in the mesosphere over Churchill, Canada. W. G. Stroud *et al.*

60-48 Present, potential, and future requirements for rotary wing all weather flight. D. B. Bennie.

60-49 The performance of ablation materials as heat protection for re-entering satellites. W. R. Warren and N. S. Diaconis.

60-50 Geophysical research using artificial earth satellites. J. F. Clark.

60-51 Criteria for control and response characteristics of helicopters and VTOL aircraft in hovering and low-speed flight. R. J. Tapscott.

60-53 The application of solid propellant rocket motors to boost space vehicles. G. Panelli.

Reports

AERODYNAMICS

BOUNDARY LAYER—*see also* COMPRESSIBLE FLOW
STABILITY AND CONTROL
THERMO-AERODYNAMICS

The velocity distribution in a turbulent boundary layer on a flat plate. R. A. Dutton. C.P. 453. 1959.
Detailed boundary layer traverses have been made in a two-dimensional turbulent boundary layer on a flat plate with zero pressure gradient. Transition was promoted by trip wires and by glass-paper strips. A constant Reynolds number per foot of $3{\cdot}9 \times 10^5$ was maintained throughout the experiments.—(1.1.3.1).

On boundary-layer transition wires. J. C. Gibbings, C.P. 462. 1959.
The effect of a single spanwise wire upon the downstream position of boundary layer transition is discussed. Arguments, based on physical reasoning, lead in the simplest case to experimental results being expressible in terms of two-dimensionless groups. The effects of free-stream turbulence, pressure gradient and Mach number upon transition very close to the wire are separately discussed. Transition downstream of the wire is also investigated and a criterion is advanced for the largest protuberance in the form of a wire that, in a specified way, does not effect transition.—(1.1.2).

Evolution of amplified waves leading to transition in a boundary layer with zero pressure gradient. P. S. Klebanoff and K. D. Tidstrom. N.A.S.A. T.N. D-195. *Sept.* 1959.
An experimental investigation of the instability of a laminar boundary layer leading to transition is presented. Waves were introduced into the boundary layer of a flat plate using the vibrating-ribbon technique, and their development and subsequent break-down were studied.—(1.1.2.1).

COMPRESSIBLE FLOW—*see also* THERMO-AERODYNAMICS
AIRCRAFT OPERATION

Investigation of variation in base pressure over the Reynolds number range in which wake transition occurs for two dimensional bodies at Mach numbers from 1·95 *to* 2·92. *V. Van Hise. N.A.S.A. T.N. D*-167. *Nov.* 1959.
Results are presented of the effects of Reynolds number upon two-dimensional base pressure throughout the Reynolds number range of wake transition. Also presented are the effects of model shape and fineness ratio. Comparisons are made with the results of the mixing theory of Crocco and Lees. Results of wake disturbance tests and wake schlieren studies are given.—(1.2.3 × 1.1.2.4).

Slender-body theory based on approximate solution of the transonic flow equation. J. R. Spreiter and A. Y. Alksne. N.A.S.A. Tech. Report R-2. 1959.
Approximate solutions of the nonlinear equations of the small disturbance theory of transonic flow are found for the pressure distribution on pointed slender bodies of revolution for flows with a free-stream Mach number of 1, and for flows that are either purely subsonic or purely supersonic. The theory is developed for bodies of arbitrary shape, and specific results are given for cone-cylinders and for parabolic-arc bodies at zero angle of attack. All results are compared either with existing theoretical results or with experimental data.—(1.2.2.1 × 22.1).

CONTROLS—*see* STABILITY AND CONTROL
FLIGHT TESTING

FLUID DYNAMICS—*see also* STABILITY AND CONTROL
THERMO-AERODYNAMICS

A study of the structure of the magnetohydrodynamic switch-on shock in steady plane motion. Z. O. Bleviss. Douglas Report S.M.-23720. *Oct.* 1959.
The structure of the steady magnetohydrodynamic switch-on shock wave is investigated for several order-of-magnitude orderings of the four diffusivities involved in the problem. The various orderings are approximated by allowing one or more of the appropriate diffusivities to approach zero, and approximate solutions that are uniformly valid to order unity are sought. Where necessary, the approximate solutions are rendered uniformly valid to first order by the insertion of boundary layers, for which the approximate equations are determined to first order. For most of the cases considered, the limiting forms of the integral curves are determined and they are sketched in appropriate three-dimensional phase spaces.—(1.4.4).

INTERNAL FLOW

Stall cell propagation in two mismatched compressor stages. R. C. Turner et al. *C.P.* 449. 1959.
An investigation into the flow fluctuations occurring in two mismatched stages in the N.G.T.E. 106 low speed compressor is described. Its purpose is to contribute to a general understanding of surging and unsteady flow phenomena in full scale compressors when operating in a mismatched condition. Hot wire anemometers were used to examine the fluctuations, measurements being made before and after each blade row at seven flow coefficients.—(1.5.1.2)

LOADS—*see also* STABILITY AND CONTROL
AEROELASTICITY

A method for calculating aerodynamic loadings on thin wings at a Mach number of 1. *J. L. Crigler. N.A.S.A. T.N. D*-96. *Nov.* 1959.
A method is presented for calculating span-load distribution at a Mach number of 1. This method differs from previously developed lifting-surface procedures in that the chordwise integrations are performed analytically. Calculated results are compared with experimentally measured data for a thin swept-back wing.—(1.6.1 × 1.10.1.2).

STABILITY AND CONTROL—*see also* FLIGHT TESTING

Wind-tunnel and piloted flight simulator investigation of a deflected-slipstream V.T.O.L. airplane, the Ryan VZ-3RY. H. A. James et al. *N.A.S.A. T.N. D*-89. *Nov.* 1959.
The characteristics of the deflected-slipstream V.T.O.L. aeroplane during a transition from hovering to normal flight were studied. The longitudinal, lateral, and directional stability and control characteristics of the vehicle were measured in the tunnel. The data were used for the simulation to document the handling qualities of the vehicle; the simulator cockpit was free to pitch and roll.—(1.8.0.1 × 1.3.8 × 1.3.4 × 1.3.7 × 29.9).

Analysis of the dynamic lateral stability of a delta-wing airplane with frequency-dependent stability derivatives. A. E. Brown and A. A. Schy. N.A.S.A. T.N. D-113. *Nov.* 1959.
An analytical investigation has been made to determine the effect of frequency-dependent stability derivatives on the lateral stability of a delta-wing aeroplane. Time histories of rolling velocity and angle of sideslip are obtained by application of the Fourier transform to solve the lateral equations of motion. In order to illustrate the frequency effects of the stability derivatives, time histories calculated by using constant values for these derivatives are presented for comparison.—(1.8.2.2).

Equations and charts for determining the hypersonic stability derivatives of combinations of cone frustrums computed by Newtonian impact theory. L. R. Fisher. N.A.S.A. T.N. D-149, *Nov.* 1959.
Equations and charts are presented from which the Newtonian impact theory values of the stability coefficients of cone frustums at small angles of attack may be determined. A procedure is outlined by means of which the coefficients for a missile shape which is made up of more than one cone frustum, or a spherical nose together with one or more cone frustums, can be estimated by impact theory.—(1.8.0.2).

Low-speed wind-tunnel tests on the de Havilland Sea Venom with blowing over the flaps. S. F. J. Butler and M. B. Guyett. R. & M. 3129. 1959.
The results of low-speed tunnel tests of longitudinal stability on a modified Sea Venom Mk. 21 fitted with blowing over the flaps are given. At each flap angle, a range of values of the sectional momentum coefficient was tested. A comparison is made between estimated and measured effects of blowing.—(1.8.2.2 × 1.3.4 × 1.1.6.1 × 3.6).

Pressure and force characteristics of noncircular cylinders as affected by Reynolds number with a method included for determining the potential flow about arbitrary shapes. E. C. Polhamus et al. *N.A.S.A. T.R. R*-46. 1959.
The low speed pressure-distribution and force characteristics of several noncircular two-dimensional cylinders were measured in a wind tunnel through a range of Reynolds numbers and flow incidences. A method of determining the potential-flow pressure distribution for arbitrary cross sections is described. Application of the data in predicting the spin characteristics of fuselages is briefly discussed.—(1.8.1.2 × 1.8.3.2 × 1.4.1 × 1.6.1).

Dynamic stability tests in hypersonic tunnels and at large model amplitudes. C. J. Welsh et al. *A.E.D.C.-T.R.*-59-24. *Dec.* 1959.
Results of experimental dynamic stability tests at Mach numbers 5, 7 and 8 of a flared afterbody re-entry shape are presented.—(1.8.2.2 × 1.12.1.3).

THERMO-AERODYNAMICS—*see also* INSTRUMENTS AND EQUIPMENT

Heat transfer measurements at a Mach number of 2 in the turbulent boundary layer on a flat plate having a stepwise temperature distribution. R. J. Conti. N.A.S.A. T.N. D-159. *Nov.* 1959.
An experimental investigation has been conducted at a Mach number of 2 to determine the effects of a step in wall temperature upon the heat transfer characteristics of a turbulent, compressible boundary layer along a flat plate having an insulated front section.—(1.9.1 × 1.2.3 × 1.1.3.4).

An analysis of the corridor and guidance requirements for supercircular entry into planetary atmospheres. D. R. Chapman. N.A.S.A. T.R. R-55. 1959.
The analysis of supercircular entry is developed around a new dimensionless parameter which combines certain conditions at the conic perigee altitude with certain characteristics of the vehicle; this parameter conveniently determines either deceleration-limited or heating-limited corridor widths for elliptic, parabolic, or hyperbolic approach trajectories. Illustrative calculations of corridor widths and the associated guidance problems are presented for Venus, Earth, Mars, Jupiter, and Titan. Generalised curves are presented for application to various entry conditions.—(1.9.1 × 25.1 × 8.2).

Heat transfer in low Reynolds number slip flow. H. C. Levey. A.R.L. Report A 112. *March* 1959.
The transfer of heat by forced convection from a hot wire in a low Mach number rarefied gas stream is investigated for small Reynolds numbers. A simple expression is found for the Nusselt number and it is suggested that this has reasonable validity over a wide range of Knudsen numbers, even into the free-molecule flow regime.—(1.9.1 × 34.3.2 × 1.4).

WINGS AND AEROFOILS—*see* LOADS
AEROELASTICITY
HYDRODYNAMICS

TESTING AND INSTRUMENTS—*see also* STABILITY AND CONTROL

A progress report on the University of Southampton hypersonic gun tunnel. K. N. C. Bray and R. A. East. C.P. 457. 1959.
A description of the mechanical construction of the tunnel and the instrumentation that has been developed for it are given, together with some preliminary measurements designed to test the steadiness and uniformity of the flow.—(1.12.1.3).

Calibration of a 40-inch continuous flow tunnel at Mach numbers 1·5 to 6. C. J. Schueler and W. T. Strike. A.E.D.C.-T.N.-59-136. *Nov.* 1959.
A test programme was conducted to calibrate the von Kármán Gas Dynamics Facility's 40 in. × 40 in., continuous, supersonic wind tunnel. Theoretical nozzle contours were adjusted, and local Mach numbers and flow angles were measured within a region of the test section. Results of the calibration at Mach numbers from 1·5 to 6 in half Mach number increments are presented. Included in the nozzle calibration programme were tests of two typical models, AGARD Calibration Model B and a 15-deg. cone cylinder.—(1.12.1.3).

AEROELASTICITY

A systematic kernel function procedure for determining aerodynamic forces on oscillating or steady finite wings at subsonic speeds. C. E. Watkins et al. *N.A.S.A. T.R. R*-48. 1959.
Details are given of a numerical solution of the integral equation which relates oscillatory or steady lift and downwash distributions in subsonic flow, the pressure distribution and some of its integrated properties for a given Mach number and frequency and for several modes of oscillation. Results of several applications are presented.—(2 × 1.6.3 × 1.10.1.2).

AIRCRAFT

See AERODYNAMICS—STABILITY AND CONTROL
FLIGHT TESTING

DESIGN AND CONSTRUCTION

See AIRPORTS

AIRCRAFT OPERATION

Theoretical investigation of the sound field produced downstream of a choked two-dimensional channel due to unsteady upstream entropy fluctuations. J. P. Appleton and H. J. Davies. C.P. 461. 1959.
The two-dimensional flow considered is that of an ideal, compressible fluid bounded by two rigid, non-conducting, parallel walls of infinite extent. A shock wave normal to the rigid boundaries divides the flow into subsonic and supersonic regimes. In the supersonic region a normal static temperature variation, which is sectionally invariant but fluctuates periodically with time, when convected through the shock wave results in a perturbation of the flow in the subsonic region. By assuming that the magnitude of the fluctuations of the static temperature are small an expression for the acoustic pressure fluctuation in the downstream part of the gas is deduced.—(5.6 × 1.2.0.1).

*The noise field from designed nozzles at different Mach numbers. J. G. M. Williams and D. C. Stevenson. C.P.*448. 1959.
Measurement of the noise radiated by unheated air jets issuing from a series of designed ½ in. exit diameter nozzles have been made for velocities covering the range 800-1800 ft./sec. Experiments were also carried out in modifying the velocity profile at the exit of the nozzle by providing a sheath of air moving at a velocity slower than the core jet from a concentric annular exit.—(5.6).

Similarity of far noise fields of jets. W. L. Howes. N.A.S.A. T.R. R-52. 1959.
Similarity parameters for far-field noise from subsonic and supersonic jets issuing from circular nozzles are derived and tested using experimental data. Relations for the total acoustic power, acoustic directivity, local mean-square-pressure spectrum, and acoustic-pressure probability-density are considered.—(5.6).

Installation notes on the precision visual glidepath (P.V.G.). R. W. Cumming et al. *A.R.L. Note H.E.*3. *July* 1959.
The Precision Visual Glidepath is an approach aid for use in moderate to good visibility which gives visual guidance in relation to an approach plane defined by two bars of lights on the ground. The design features of the aid and its installation are described, and how it might be set up in "difficult" locations is shown.—(5.3 × 5.5).

AIRPORTS

Statistical measurements of contact conditions of commercial transports landing on airports at an altitude of 5,300 feet and at sea level. N. S. Silsby and S. P. Livingston. N.A.S.A. T.N. D-147. *Nov.* 1959.
A comparison is made of the statistical landing contact conditions for 170 commercial-transport landings during routine daytime operations at a mile-high airport and at a sea-level airport to determine the effect of altitude on the contact conditions of vertical velocity, air speed, bank angle, rolling velocity, and distance of the touchdown point from the runway threshold.—(6.1 × 33.1.2 × 4.2.5.1).

EXTRA-ATMOSPHERIC TECHNOLOGY

See also AERODYNAMICS—THERMO-AERODYNAMICS

1958 *N.A.S.A./U.S.A.F. Space Probes* (*Able*-1). *Final Report Vol.* 2. *Payload and experiments. Space Technology Laboratories Inc. N.A.S.A. Memo* 5-25-59*W. T.I.L.* 6577. *June* 1959.
The three N.A.S.A./U.S.A.F. lunar probes of August, October and November 1958 are described. Details of the programme,

vehicles, payloads, firings, tracking, and the results are presented.—(8.2 × 25 × 27.3.1).

1958 *N.A.S.A./U.S.A.F. Space Probes* (*Able*-1). *Final Report Vol.* 3. *Vehicles, trajectories, and flight histories. Space Technology Laboratories Inc. N.A.S.A. Memo* 5-25-59*W. T.I.L.* 6578. *June* 1959.—(8.2 × 25 × 27.3.1).

Some thrust and trajectory considerations for lunar landings. R. J. Weber and W. M. Pauson. N.A.S.A. T.N. D-134. *Nov.* 1959.
A proposed method for accomplishing soft landings on the moon is first to establish a circumular orbit and then to transfer to the lowest acceptable altitude by a minimum-energy elliptical path. After braking to a halt, a vertical descent is made consisting of free fall and a final upward thrust application to decelerate the vehicle. The effects of trajectory errors and thrust level are discussed.—(8.2).

Nearly circular transfer trajectories for descending statellites. G. M. Low. N.A.S.A. Tech. Report R-3. 1959
Simplified expressions describing the transfer from a satellite orbit to the point of atmospheric entry are derived. The expressions are limited to altitude changes that are small compared with the earth's radius, and velocity changes small compared with satellite velocity, They are further restricted to motion about a spherical, nonrotating earth. The transfer trajectory resulting from the application of thrust in any direction at any point in an elliptic orbit is considered. Expressions for errors in distance and entry angle due to an initial misalignment and magnitude error of the deflecting thrust are presented. The guidance and accuracy requirements to establish a circular orbit, and orbit corrections are also discussed.—(8.2 × 25.1 × 25.2).

FLIGHT TESTING

Preliminary tests at low speed of leading edge modifications on the Avro 707*A. P. B. Atkins and R. R. Green. A.R.L. Tech. Memo. F.*11. *Sept.* 1959.
Some drag and spanwise pressure distribution measurements have been used to supplement pilot's reports on the low speed handling characteristics of the AVRO 707A delta aircraft with roughness and turbulators applied to a portion of the under surface near the leading edge.—(13.2 × 1.8.2.1 × 1.3.7 × 3.6).

FUELS AND LUBRICANTS

Lubrication of corrosion-resistant alloys by mixtures of halogen-containing gases at temperatures up to 1200°*F. D. H. Buckley and R. L. Johnson. N.A.S.A. T.N. D*-197. *Nov.* 1959.
CF_2Br_2, CF_3Br, CHF_2Br, and SF_6 gases were used to lubricate nickel- and cobalt-base alloys at temperatures up to 1200°F. Reaction mechanisms in "reactive" gas lubrication were used to select suitable metal-gas combinations for lubrication systems.—(14.3).

Heterogenous combustion of multicomponent fuels. B. J. Wood et al. *N.A.S.A. T.N. D*-206. *Nov.* 1959.
A study was made of the combustion characteristics of a fuel drop containing liquid constituents of different physical and chemical properties.—(14.3 × 34.1.1).

HYDRODYNAMICS

Investigation of a high-speed hydrofoil with parabolic thickness distribution. V. E. Johnson and T. A. Rasnick. N.A.S.A. T.N. D-119. *Nov.* 1959.
The hydrofoil design incorporates meanline camber with a parabolic thickness distribution. An aspect ratio 1 model of the cambered-parabolic section with a base thickness of 0·1 chord was investigated at a depth of 0·5 chord for a range of angles of attack from 1° to 8° and speeds from 130 to 190 ft./sec.—(17.2 × 1.10.1.1).

A hydrodynamic investigation of the effect of adding upper-surface camber to a submerged flat plate. V. L. Vaughan. N.A.S.A. T.N. D-166. *Nov.* 1959.
Hydrodynamic tests were made on three models at a constant depth of submersion of 6 in. at non-cavitating and non-ventilating speeds. Comparisons between these data and data on two rectangular modified flat plates having aspect ratios of 0·25 with different thicknesses are presented.—(17.2 × 1.10.2.1).

INSTRUMENTS AND EQUIPMENT

Notes on a thermal fluxmeter. J. Plenier. R.A.E. Lib. Trans. 843. *Oct.* 1959.
An instrument to measure the thermal flux generated by infra-red radiant heating installations used to simulate kinetic heating of aircraft structures is described. The theory, construction, calibration and performance of the instrument are fully described and possible improvement are discussed.—(18.1 × 34.2.2 × 1.9.1).

Direct measurement of power spectra by an analog computer. T. H. Wonnacott. N.R.C. Report M.K.-5. Sept. 1959.
The power spectral density (spectrum) of a continuous random process is estimated in the most natural way: the record is passed through a filter selecting frequencies close to f_0, then squared, and the resulting "power" is averaged to give an estimate of the spectrum at f_0. The random nature of the record implies that this spectrum estimator is also a random variable, and its variation is investigated. The analysis often parallels that of the digital analysis of a discrete time series. As an example the spectrum of band-limited white Gaussian noise is measured.—(18.1).

Requirements for a hybrid analog-digital computer. D. C. Baxter and J. H. Milsum. N.R.C. Report M.K.-7. Oct. 1959.
Conventional analog and digital computers are critically compared as to their relative suitability for scientific and engineering problems.—(18.1).

MATERIALS

Investigation of aluminum phosphate coatings for thermal insulation of airframes. A. G. Eubanks and D. G. Moore. N.A.S.A. T.N. D-106. *Nov.* 1959.
Coatings bonded with aluminium phosphate were investigated for possible use as thermal insulation on airframes. The heavier applications were reinforced with expanded S.A.E. 1020 carbon steel spot-welded to the base metal.—(21.3.1 × 21.4).

Tensile properties of 6*A*1-4*V titanium-alloy sheet under rapid-heating and constant-temperature conditions. H. L. Price. N.A.S.A. T.N. D*-121. *Nov.* 1959.
Yield strength and rupture strength, obtained from rapid-heating tests, are compared with yield and tensile strengths of elevated-temperature tensile stress-strain tests for ½ hour exposure. Results of some conventional tensile creep tests are presented. A temperature-rate parameter was used to construct master curves from which stresses and temperatures for yield and rupture can be predicted. Yield temperatures under rapid-heating and constant-load conditions at temperature rates from 0·2°F. to 100°F. per second were calculated from phenomenological relation between stress, strain rate, and temperature.—(21.2.1)

MATHEMATICS

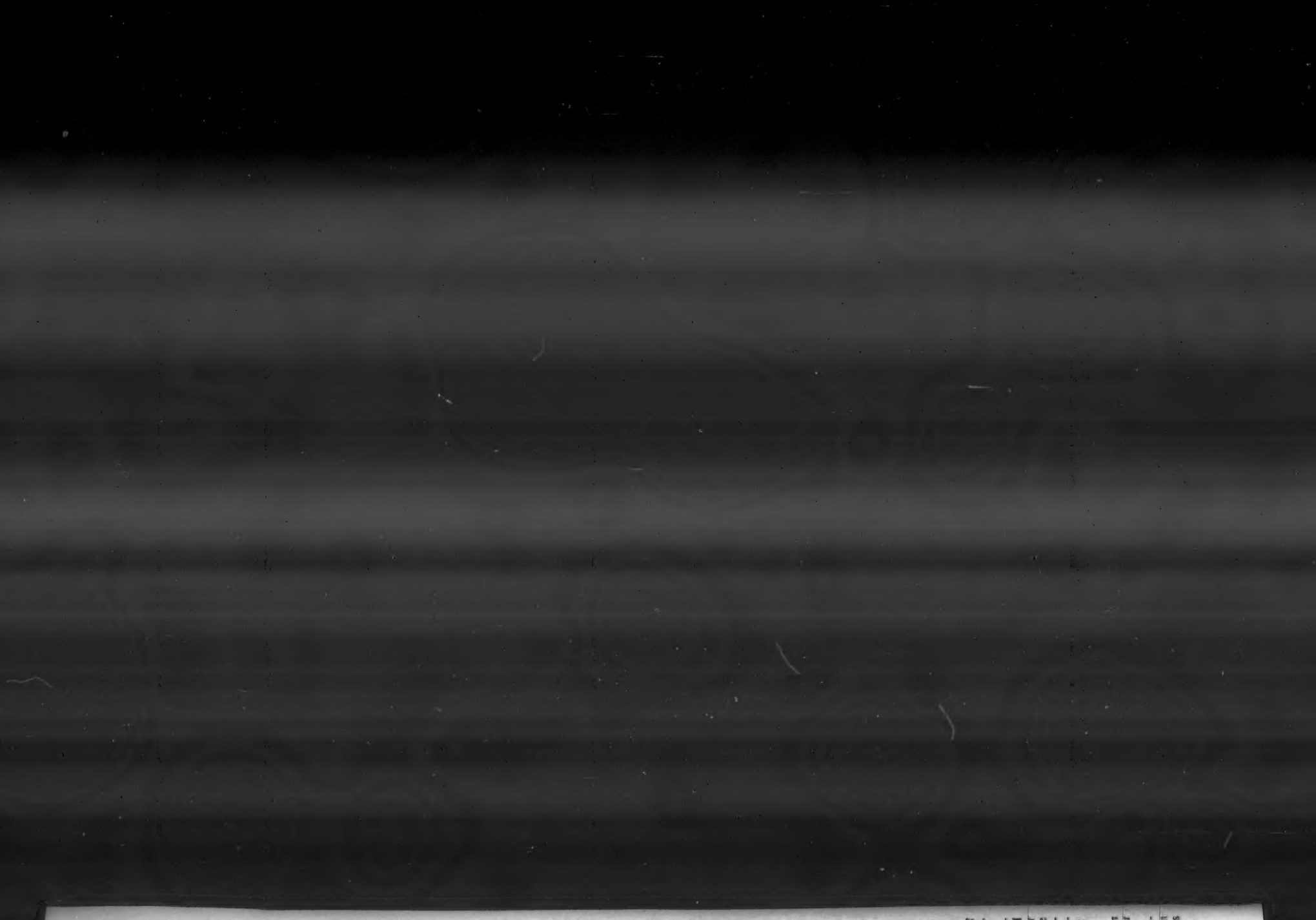
See AERODYNAMICS—COMPRESSIBLE FLOW

MISSILES

See AERODYNAMICS—THERMO-AERODYNAMICS
EXTRA-ATMOSPHERIC TECHNOLOGY

POWER PLANTS

See also EXTRA-ATMOSPHERIC TECHNOLOGY

A high-performance 250*-pound-thrust rocket engine utilizing coaxial-flow injection of JP-4 fuel and liquid oxygen. S. Stein. N.A.S.A. T.N. D*-126. *Oct.* 1959.
A high-performance engine possessing new features of combustion-chamber fabrication and injector-head design was developed as a result of the need for small rocket engines suitable for use in wind tunnel missile and vehicle-booster models. The design features and performance tests are described for a precision-cast combustor and an injector head having jets concentrated in the central part of the injection face.—(27.3 × 34.1.1).

Static force tests of several annular jet configurations in proximity to smooth and irregular ground. E. E. Davenport et al. *N.A.S.A. T.N. D*-168. *Nov.* 1959.
The investigation was undertaken to investigate the effectiveness of a discontinuous annulus, the effects of changing from circular to elliptical plan forms, and the effects of irregularities in the ground at zero forward speed.—(27.1.1).